Searching for Heavy Leptophilic Z' : *from Muon Collider* *to Gravitational Waves*

Si Wang

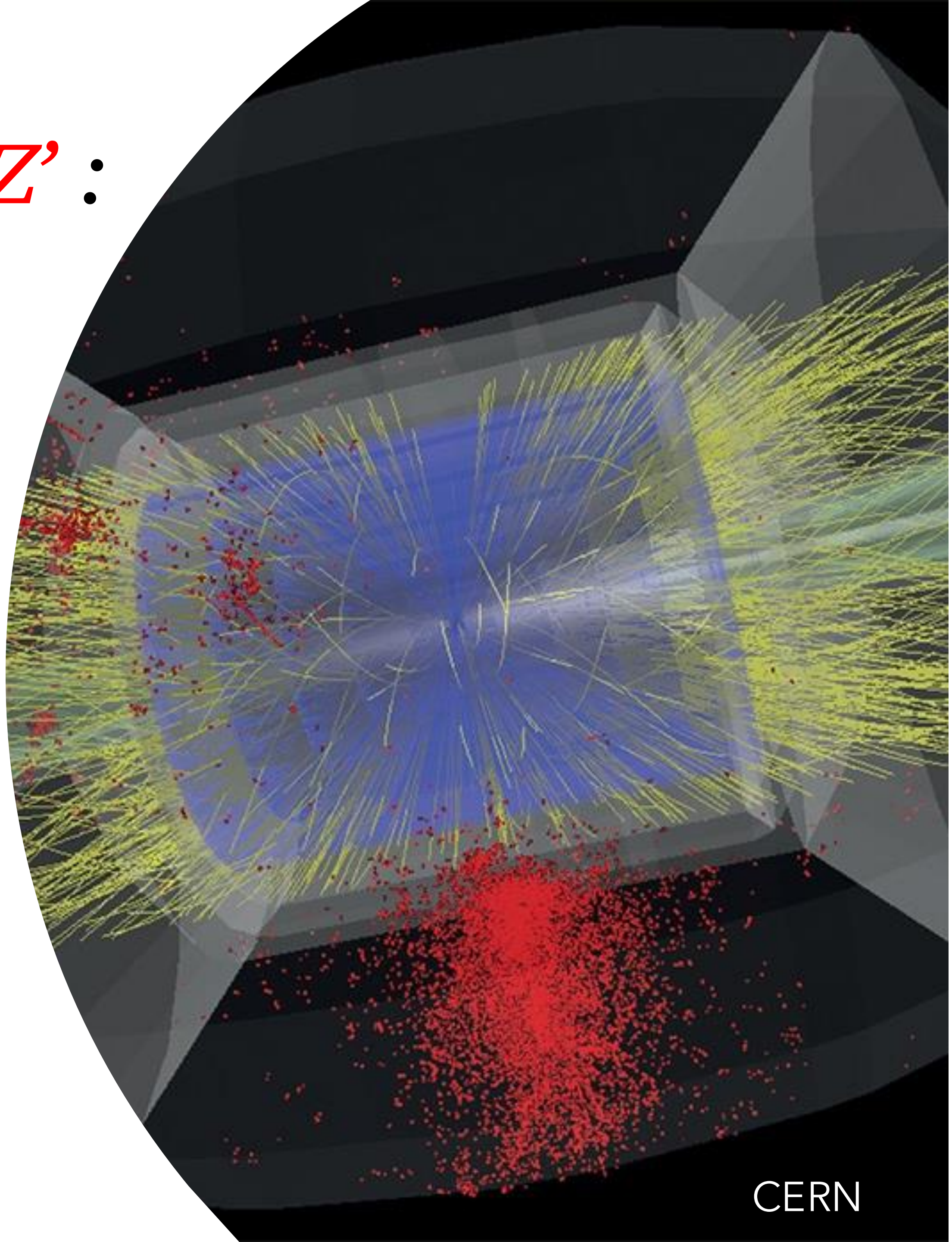
University of Pittsburgh

Nov 7, 2024

Collaborators:

A. Dasgupta, P.S. B. Dev, T. Han, R. Padhan, K. Xie

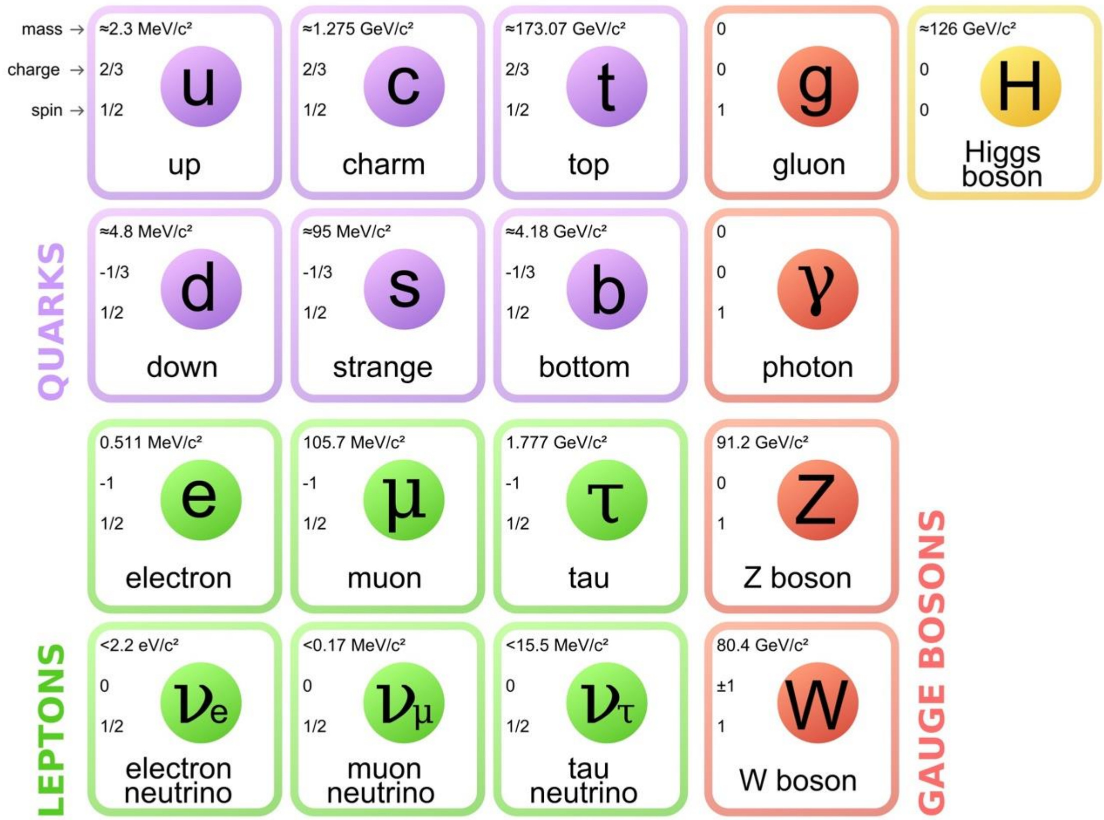
arXiv: 2308.12804



Outline

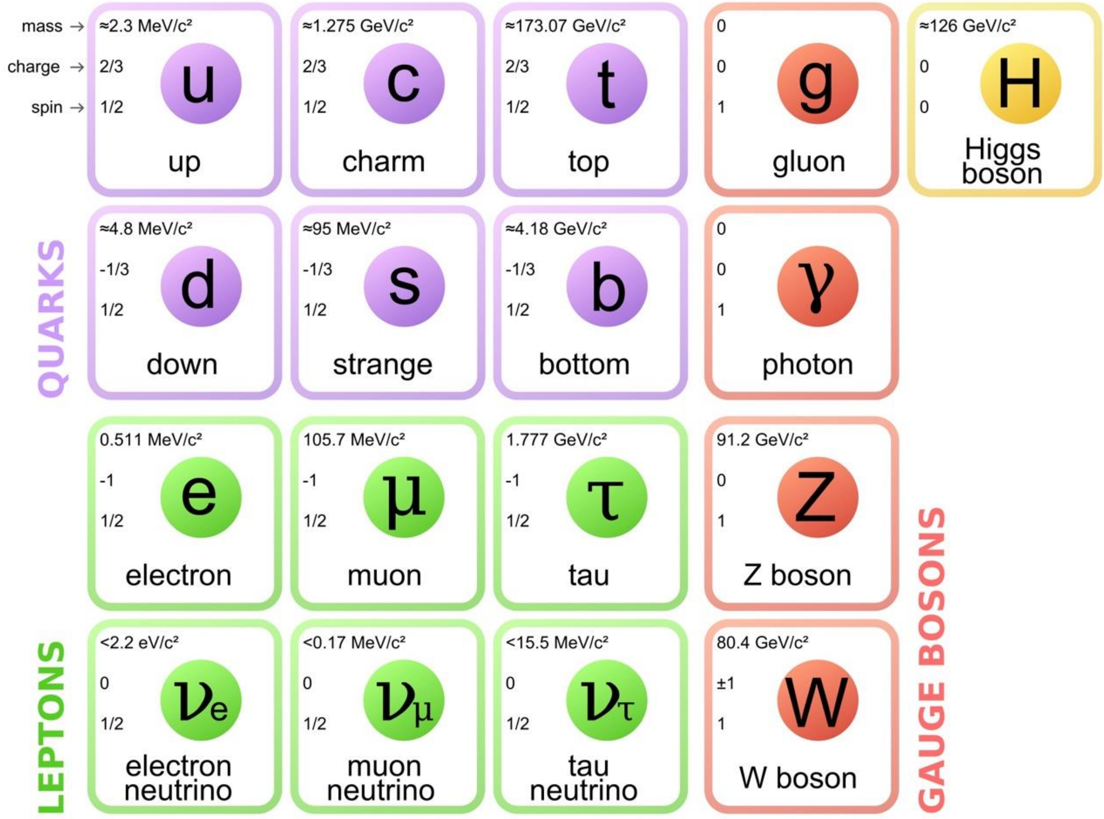
- Gauge U(1) Model and Z' particle
- Muon Collider Search
- Gravitational Waves from first order phase transition

The Standard Model



(image credit: quantum diaries)

The Standard Model



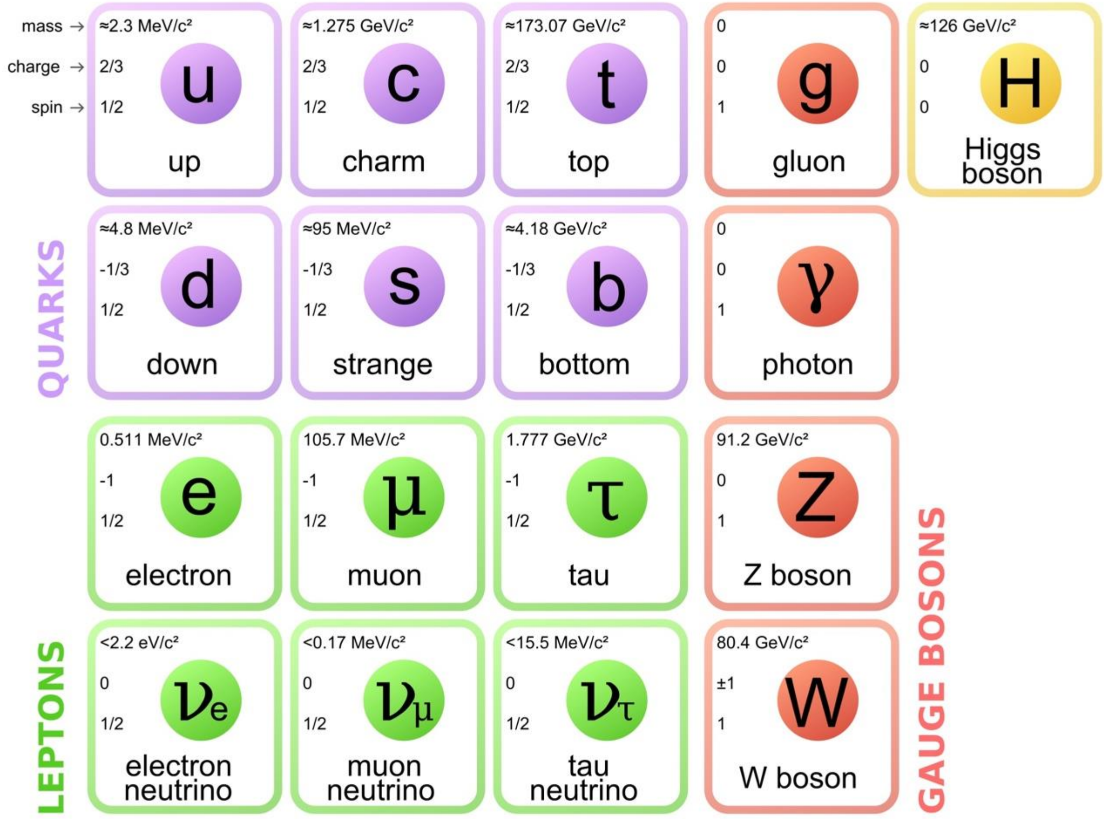
(image credit: quantum diaries)

The Success of Standard Model:

- Prediction and discovery of W, Z, t, H
- Precision Measurement of Electroweak

……

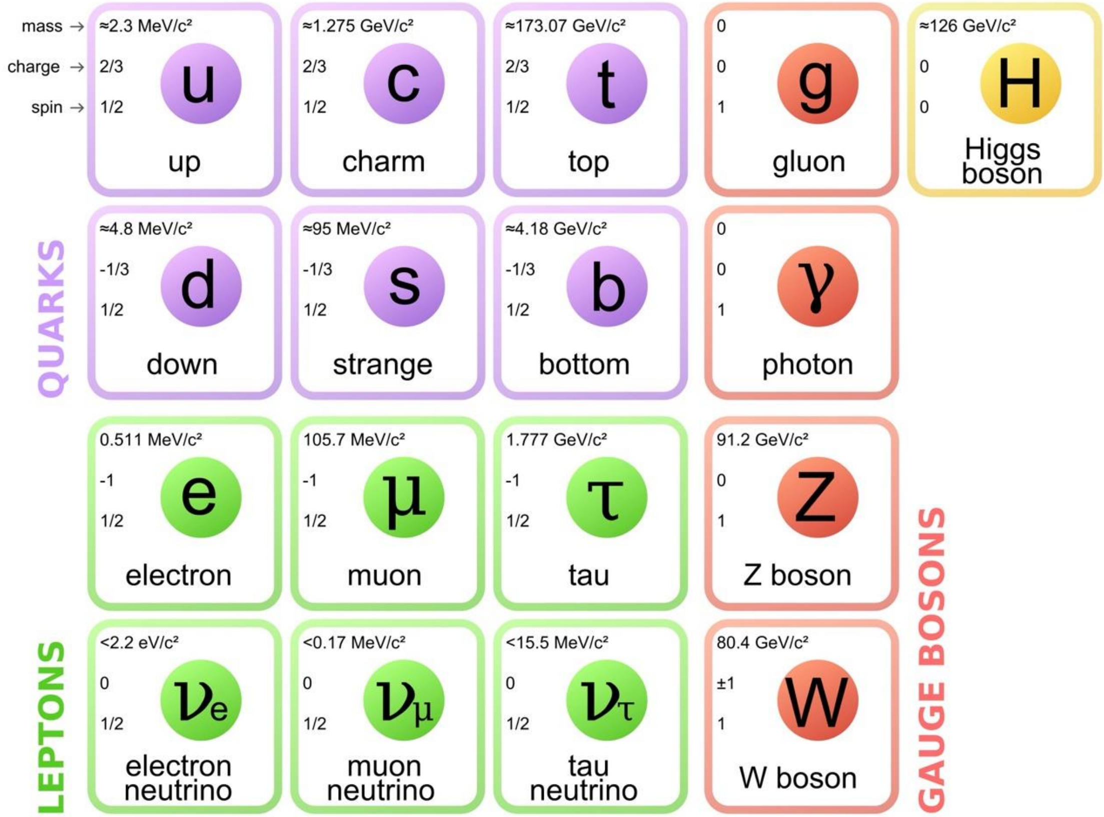
The Standard Model



(image credit: quantum diaries)

Is Standard Model the Final Theory?

The Standard Model

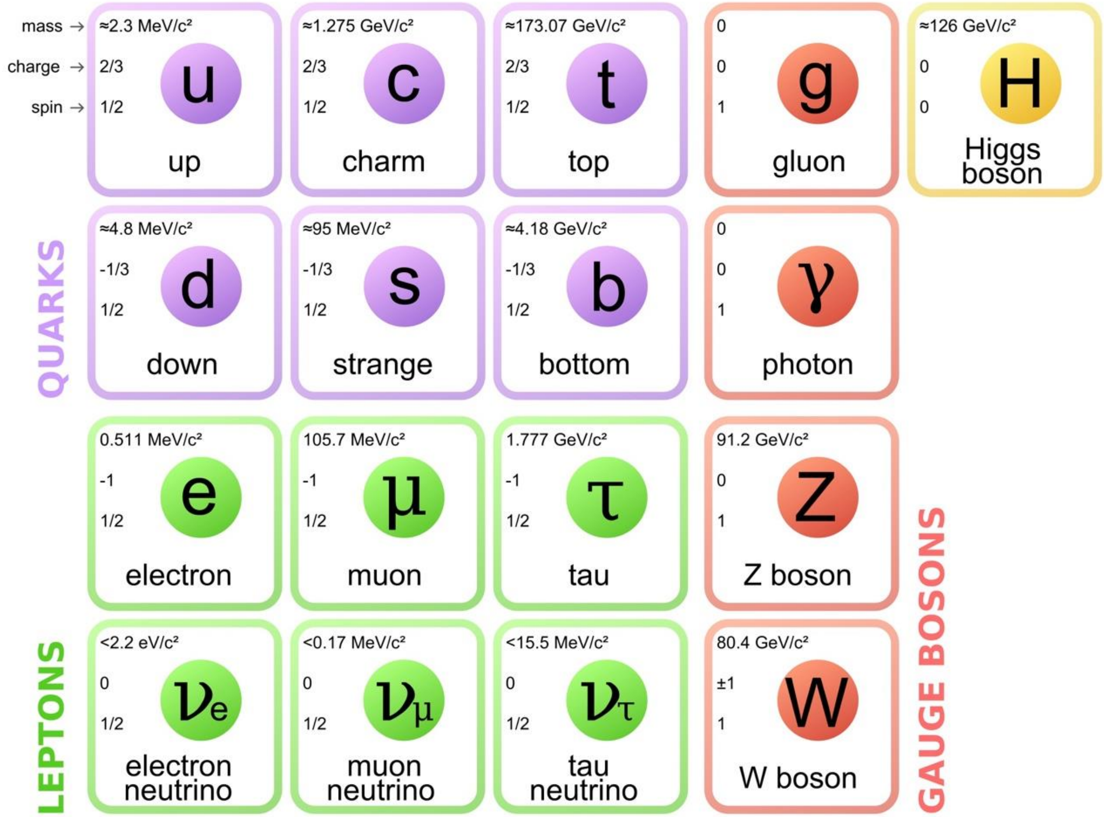


(image credit: quantum diaries)

Is Standard Model the Final Theory?

- Certainly not!

The Standard Model



(image credit: quantum diaries)

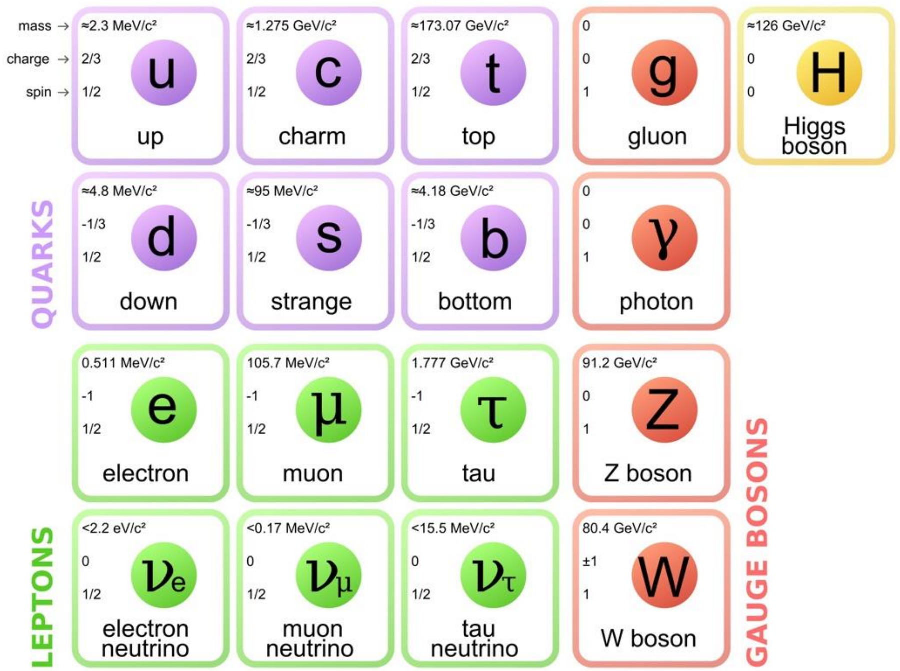
Is Standard Model the Final Theory?

- Certainly not!

- Dark Matter
- Neutrino Masses
- Matter-Antimatter Asymmetry
- ……

The Model Symmetries

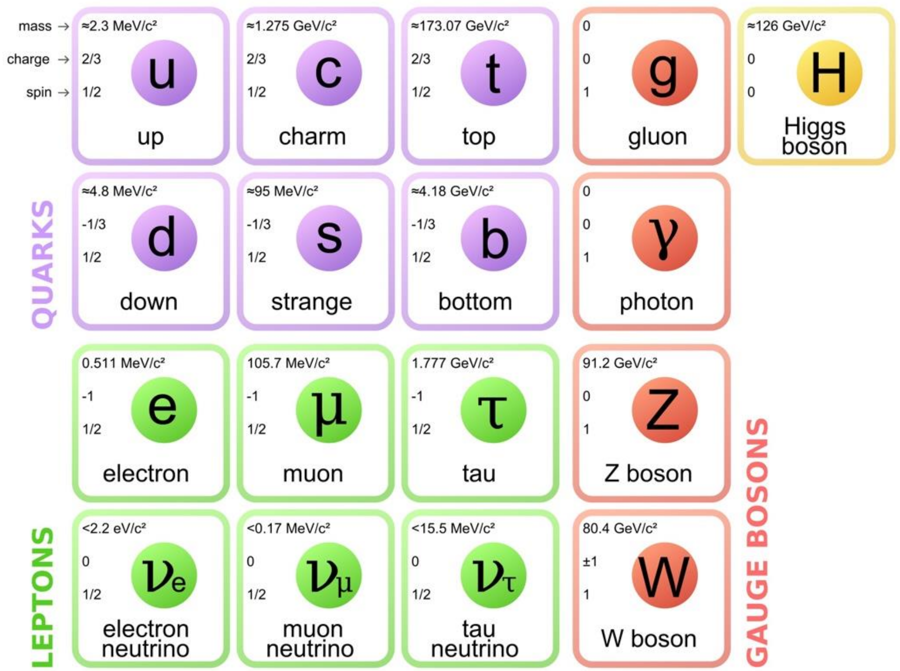
- The SM Symmetries:
- $SU(3)_C \times SU(2)_L \times U(1)_Y$



The Model Symmetries

- Extra Symmetry:

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

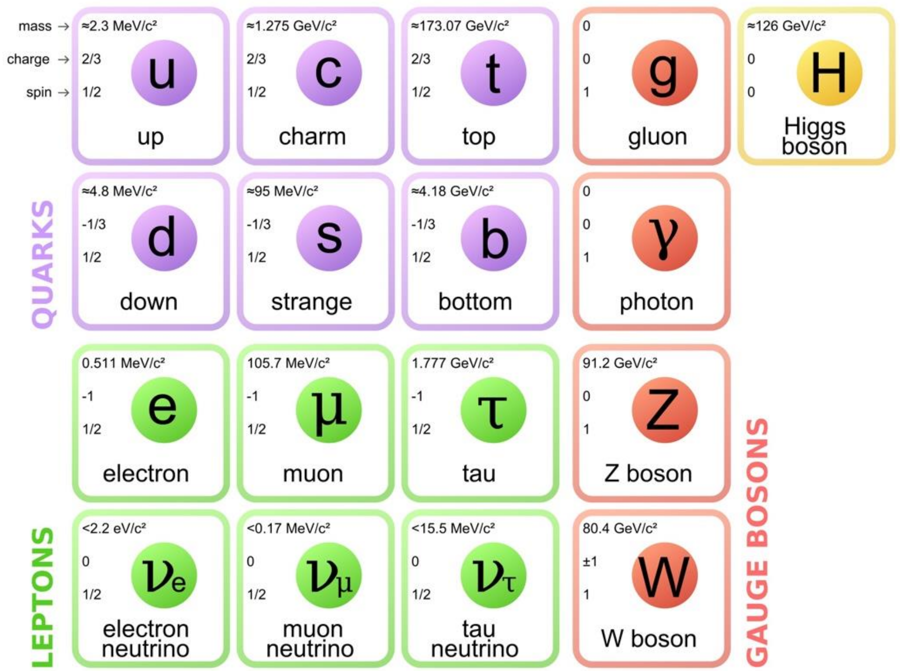


The Model Symmetries

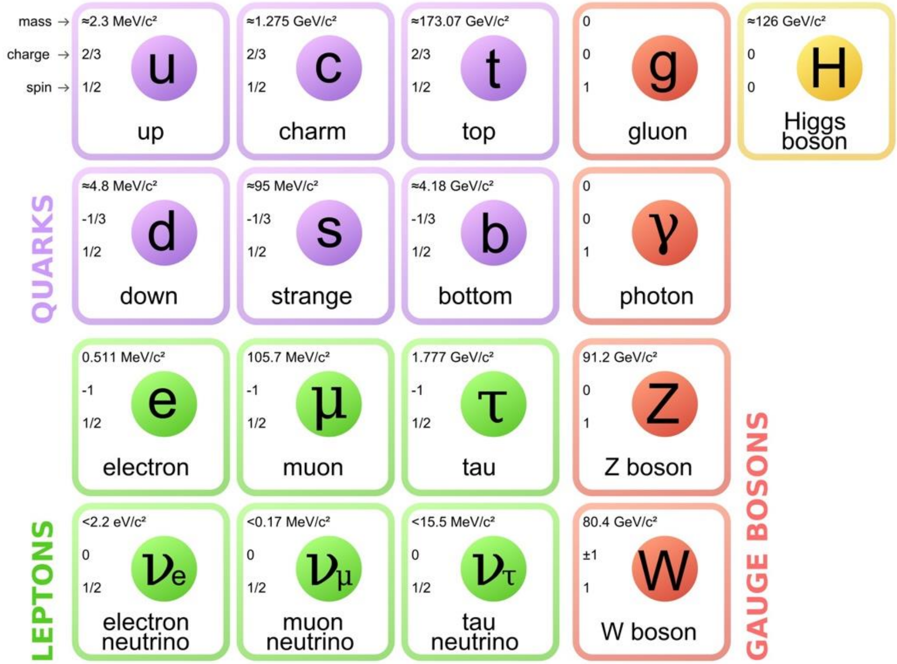
- Extra Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

- What are the consequences of the new symmetry?



The Model Symmetries



- Extra Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

- What are the consequences of the new symmetry?

Z' New gauge boson, Propagator of New force, Leptophilic

Φ to produce the Z′ mass

Why Studying this Model ?

- Simplest Extension → Searching New Particles at Colliders

  [G.Huang, F.S.Queiroz, W.Rodejohann, arXiv:2101.04956]

Why Studying this Model ?

- Simplest Extension → Searching New Particles at Colliders

  [G.Huang, F.S.Queiroz, W.Rodejohann, arXiv:2101.04956]

- Anomalous Magnetic Dipole Moment $(g-2)_\mu$

  [P. Fayet, arXiv:hep-ph/0702176]

Why Studying this Model ?

- Simplest Extension → Searching New Particles at Colliders

  [G.Huang, F.S.Queiroz, W.Rodejohann, arXiv:2101.04956]

- Anomalous Magnetic Dipole Moment $(g-2)_\mu$

  [P. Fayet, arXiv:hep-ph/0702176]

- Gravitational Waves Generation

  [R. Jinno, M. Takimoto, arXiv: 1604.05035]

Why Studying this Model ?

- Simplest Extension → Searching New Particles at Colliders

  [G.Huang, F.S.Queiroz, W.Rodejohann, arXiv:2101.04956]

- Anomalous Magnetic Dipole Moment $(g-2)_\mu$

  [P. Fayet, arXiv:hep-ph/0702176]

- Gravitational Waves Generation

  [R. Jinno, M. Takimoto, arXiv: 1604.05035]

- Mediator to the Dark Sector

  [W. Altmannshofer, S. Gori, S. Profumo, F. S. Queiroz, arXiv: 1609.04026]

Model B-L

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

Model B-L

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
q_L	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
l_L	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1

Fermion content and charges for the $B-L$ model.

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
H	1	2	$\frac{1}{2}$	0
χ	1	1	0	2

Scalar content and charges for the $B-L$ model.

[Basso, Belyaev, Moretti, Shepherd-Themistocleous(2008)]

$L_\mu - L_\tau$ Model

B-L model Variant:

$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ Models

Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**2**	**2**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2

$L_\mu - L_\tau$ Model

B-L model Variant:

$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ Models

Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**2**	**2**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2

$$\mathcal{L}_{\mu-\tau} = g' Z'_\nu (\bar{L}_\mu \gamma^\nu L_\mu - \bar{L}_\tau \gamma^\nu L_\tau + \bar{\mu_R} \gamma^\nu \mu_R - \bar{\tau_R} \gamma^\nu \tau_R) + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu$$

$$M_{Z'} = 2 g' v_\Phi$$

New coupling

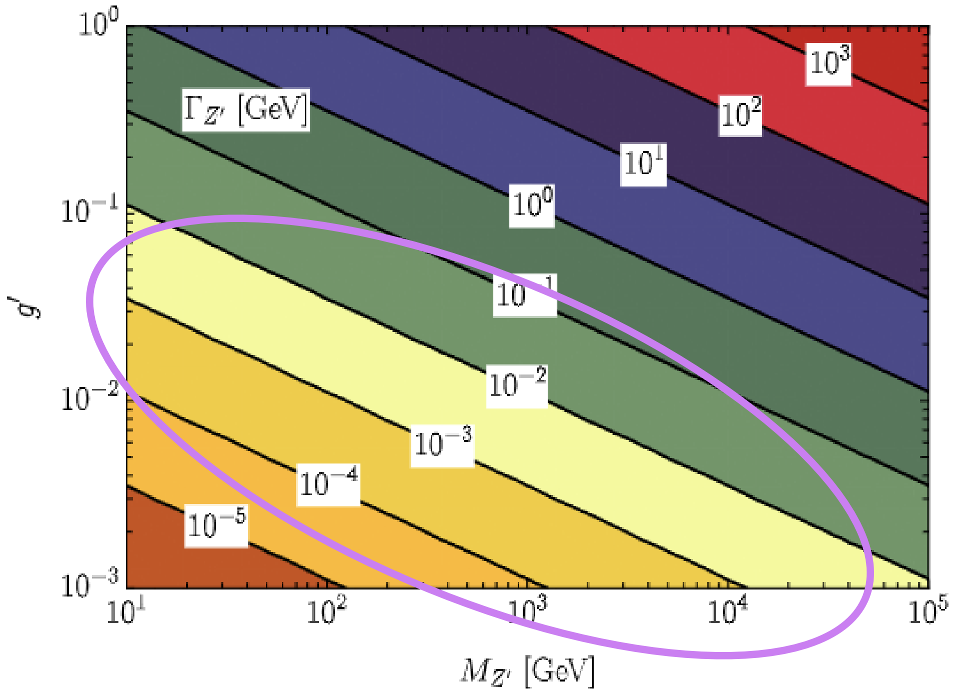
Z’ Particle

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

Ignore lepton masses

$$\Gamma(Z' \to l\bar{l}) = 2\Gamma(Z' \to \nu\bar{\nu})$$

$$\Gamma_{tot} = \frac{(2N_l + N_\nu)g'^2}{24\pi} M_{Z'} = \frac{6g'^2}{24\pi} M_{Z'}$$



Z' Particle

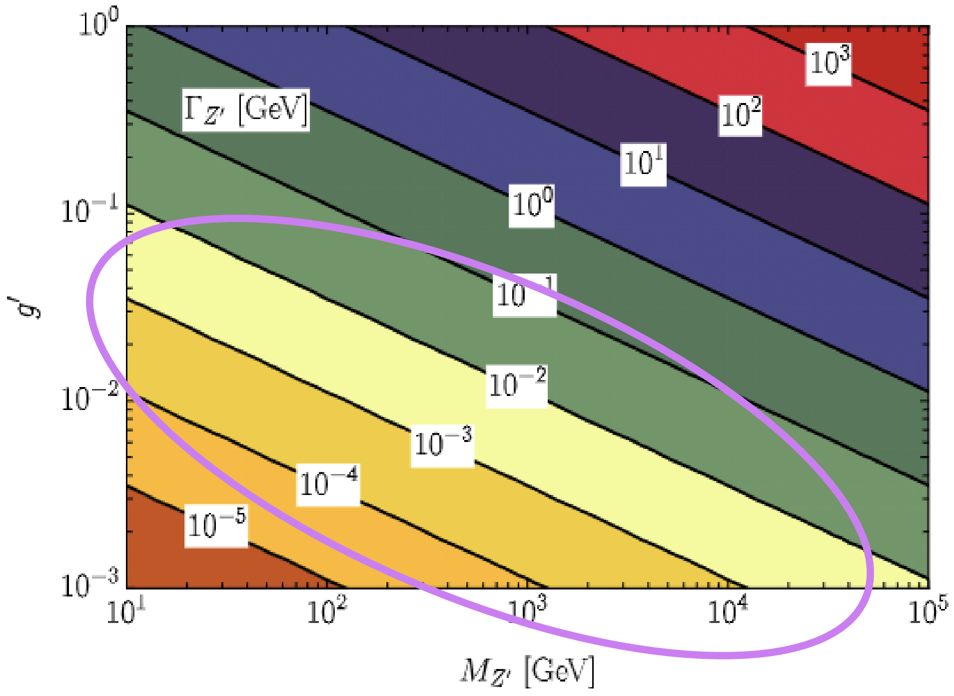
No RH LH difference

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

Ignore lepton masses

$$\Gamma(Z' \to l\bar{l}) = 2\Gamma(Z' \to \nu\bar{\nu})$$

$$\Gamma_{tot} = \frac{(2N_l + N_\nu)g'^2}{24\pi} M_{Z'} = \frac{6g'^2}{24\pi} M_{Z'}$$



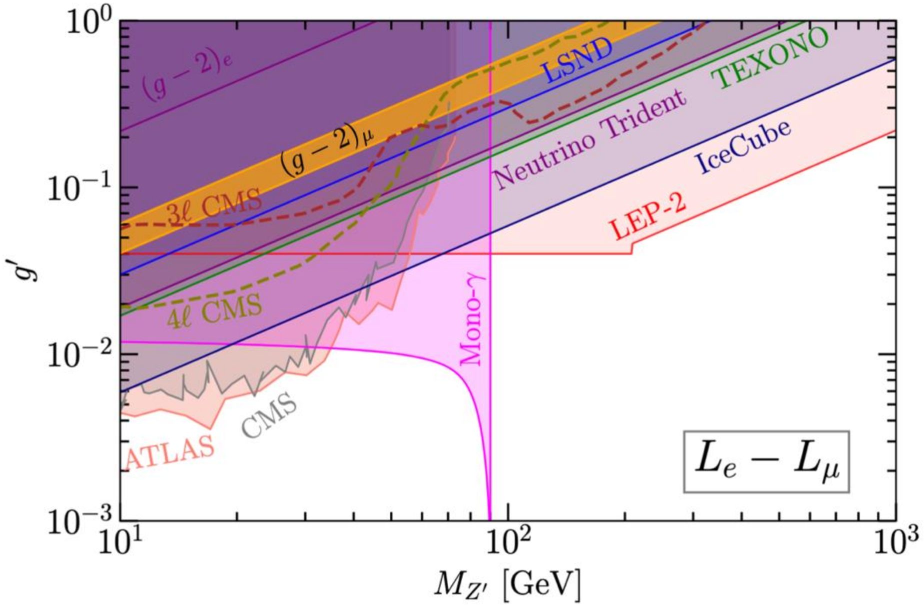
Proper decay length:

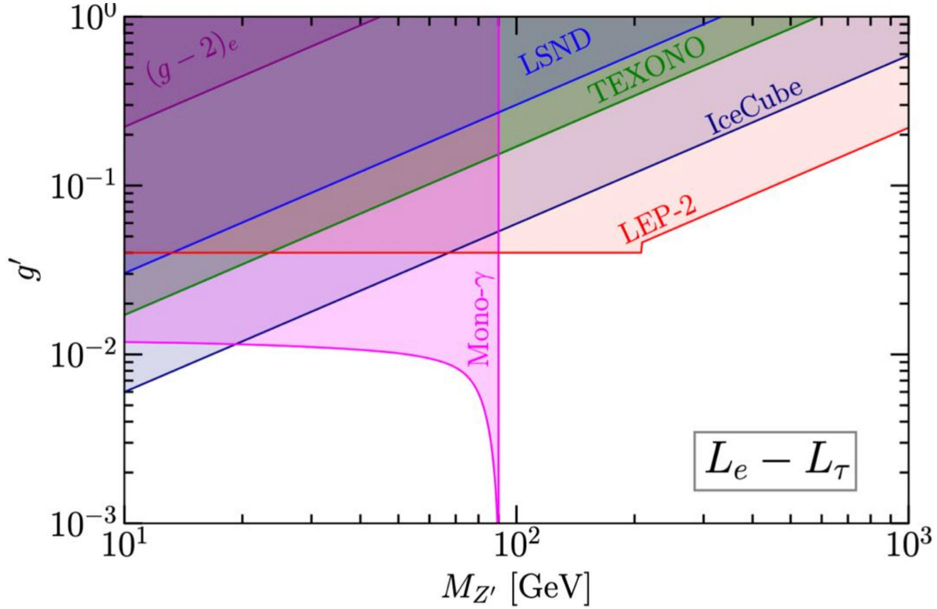
$$c\tau = \frac{c}{\Gamma(Z')} = 2.48 \times 10^{-4}\ \mu m \left(\frac{10^{-3}}{g'}\right)^2 \left(\frac{10\ \text{GeV}}{M_{Z'}}\right)$$

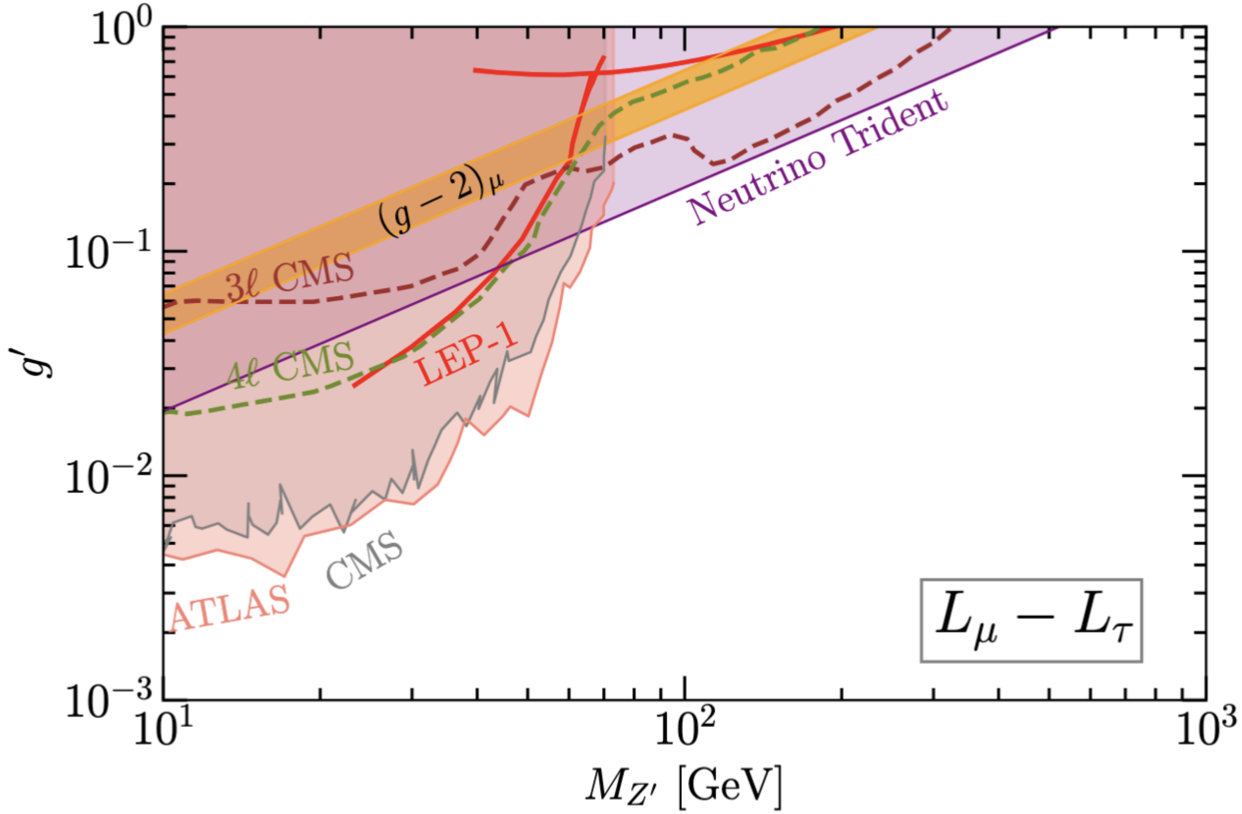
Prompt decay

Current Constraints

Current Exclusion Bounds







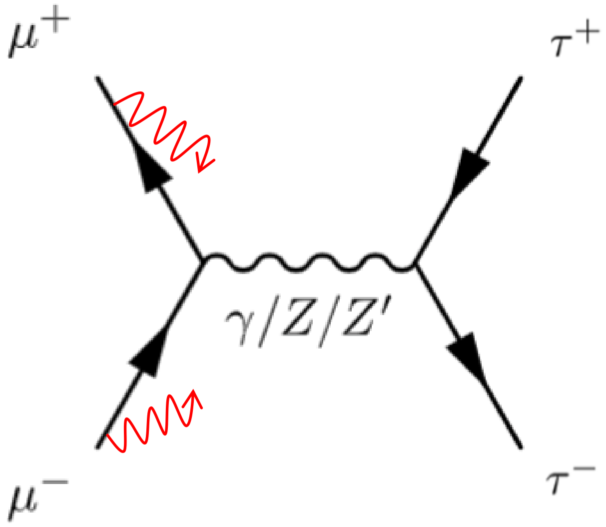
Current:

LHC: ATLAS, CMS
Neutrino scattering: LSND,TEXONO
LEP, IceCube, $(g-2)_l$

Muon Collider Searching

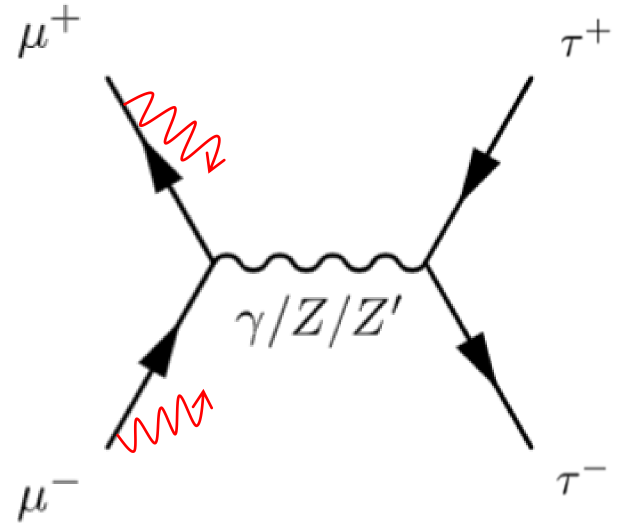
Z' Particle On-Shell (resonance) Production

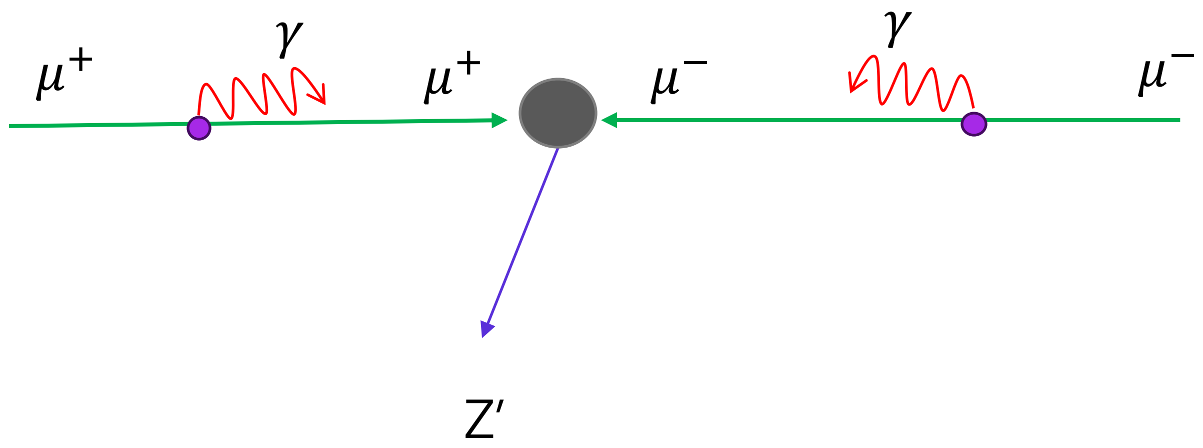
$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



Z' Particle On-Shell (resonance) Production

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



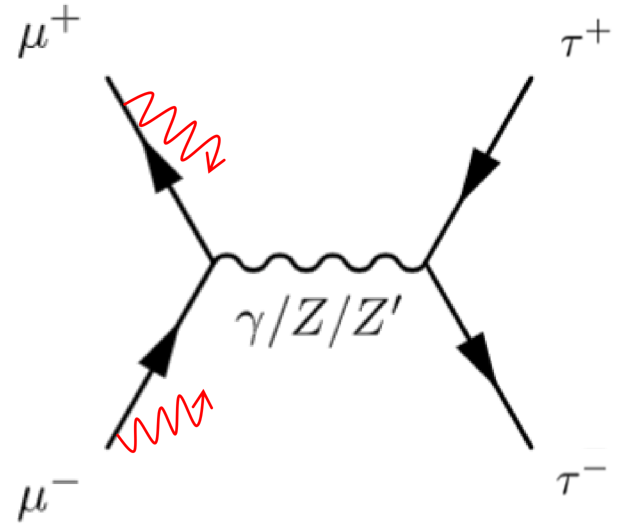


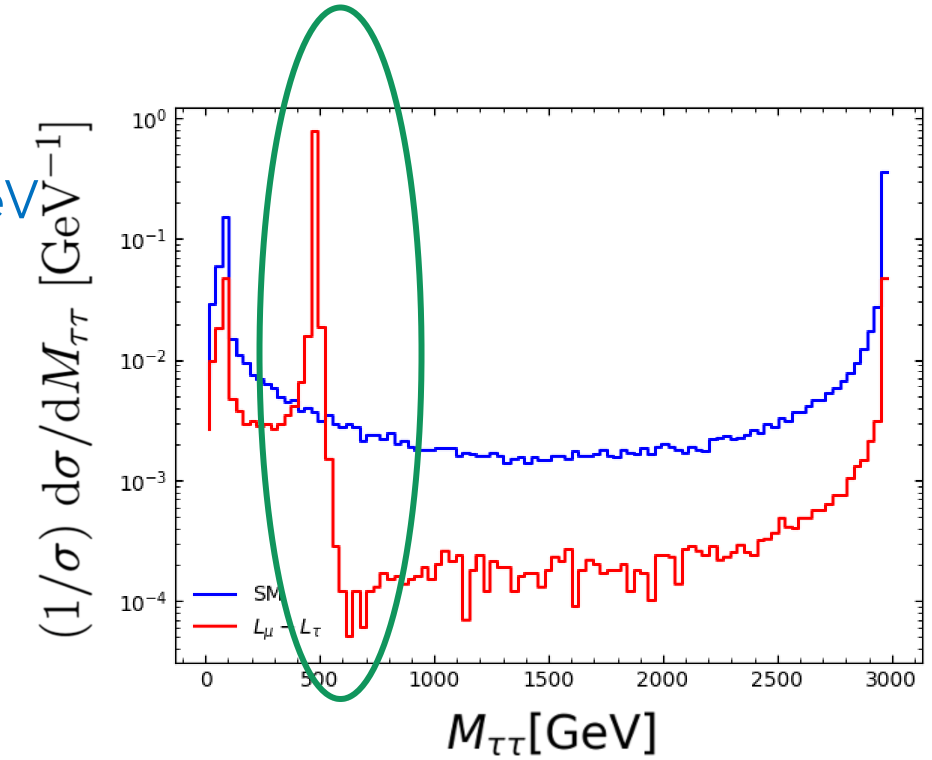
$$E^2 = p^2 + m^2$$

Z' Particle On-Shell (resonance) Production

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)

$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2





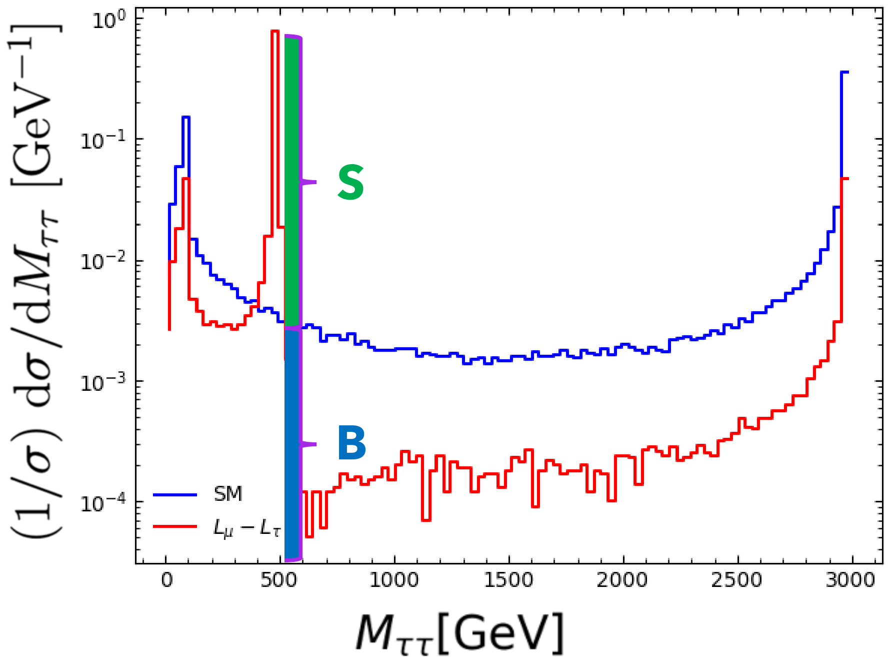
propagator:

$$\frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2\Gamma^2} \longrightarrow \text{peak}$$

Z' Particle On-Shell (resonance) Production

Sensitivity

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

For $M_{Z'}$, from 100 GeV to 3TeV

Significance:

$$\mathcal{S} = \frac{S}{\sqrt{S + B + \delta^2 (S+B)^2}} = 2$$

(equivalent to 95% CL)

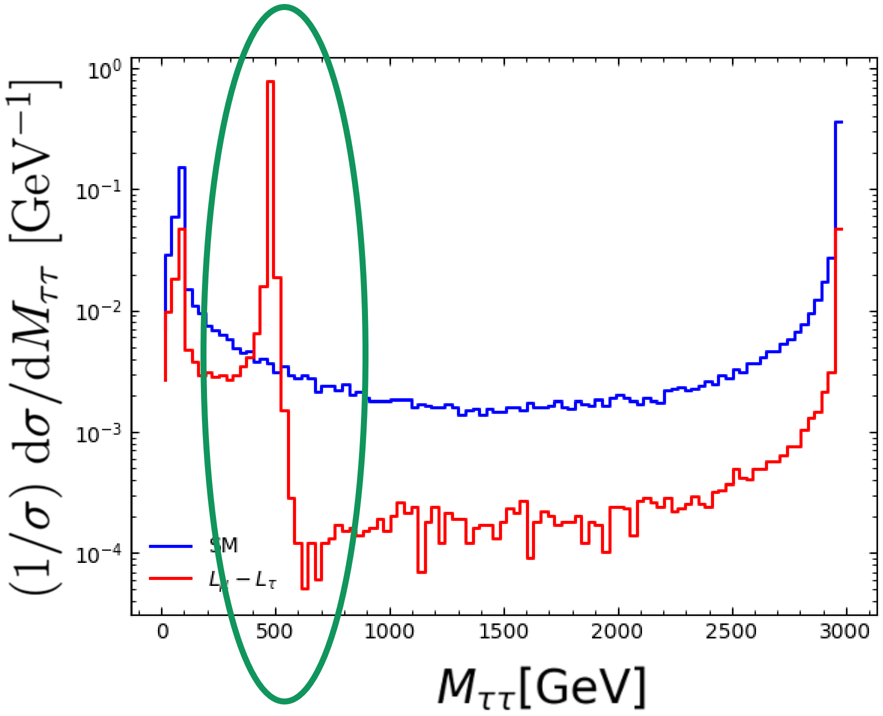
S = $N^{SM+Z'} - N^{SM} = \epsilon\, \mathcal{L}\left(\sigma^{SM+Z'} - \sigma^{SM}\right)$

B = $N^{SM} = \epsilon\, \mathcal{L}\, \sigma^{SM}$

Whizard

Z' Particle On-Shell (resonance) Production   Selection Cuts

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g'=0.2

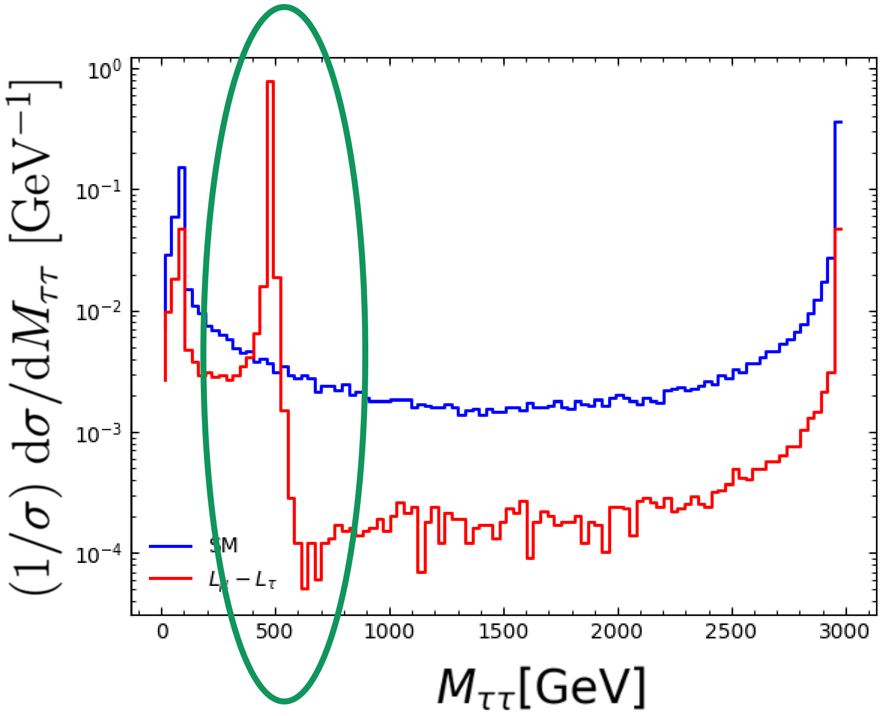
Pre-selection Cuts:

$$p_T^\ell > 30\ \mathrm{GeV},\ \ |\eta_\ell| < 2.44,\ \ \Delta R_{\ell\ell} > 0.3$$

Z' Particle On-Shell (resonance) Production

Selection Cuts

$\mu^+\mu^- \to \tau^+\tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3$ TeV

$M_{Z'} = 500$ GeV

g′=0.2

Pre-selection Cuts:

$$p_T^\ell > 30\ \mathrm{GeV},\ \ |\eta_\ell| < 2.44,\ \ \Delta R_{\ell\ell} > 0.3$$

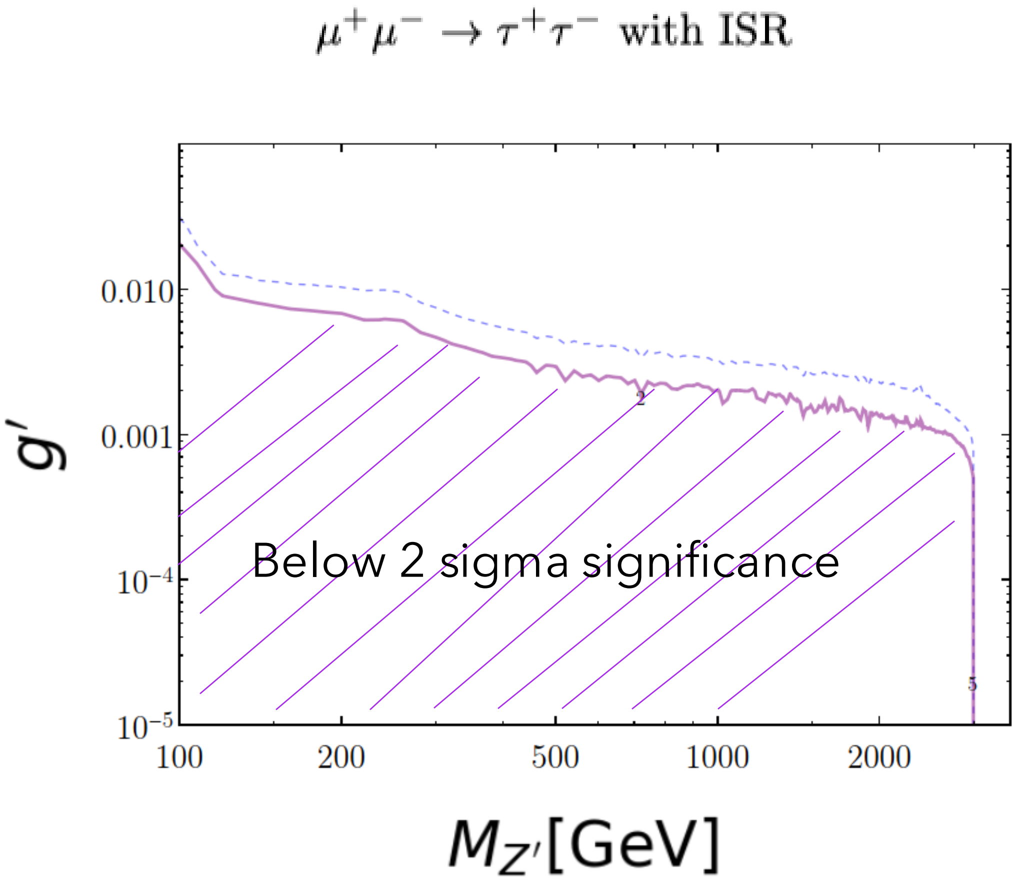
Optimization Cuts:

$$|M_{\ell\ell} - M_{Z'}| < 0.05 M_{Z'}$$

τ

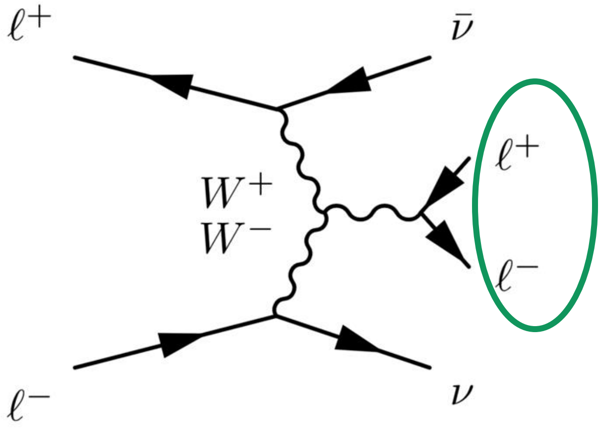
Z’ Particle On-Shell (resonance) Production

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$

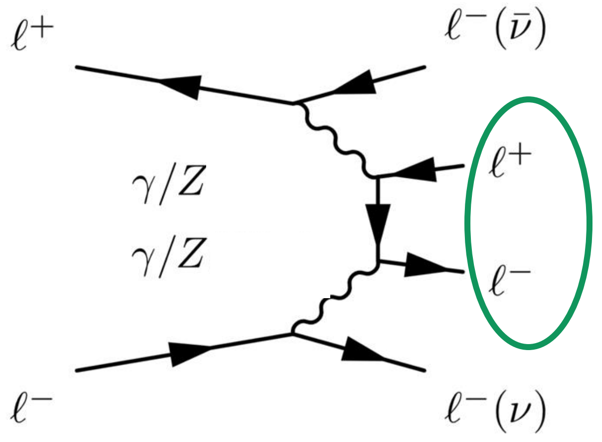


Exclusion(2σ) and Discovery(5σ) lines

Vector Boson Fusion (VBF) Background

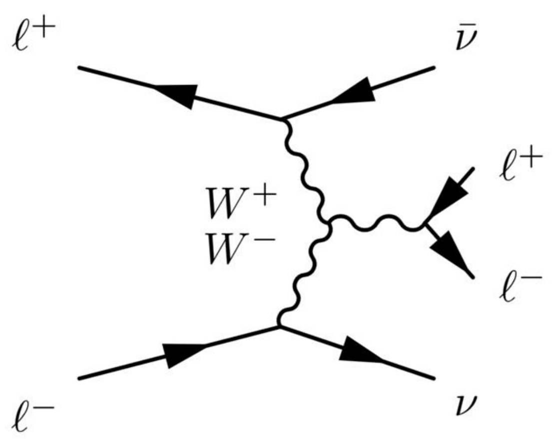


Charge Current (CC) VBF

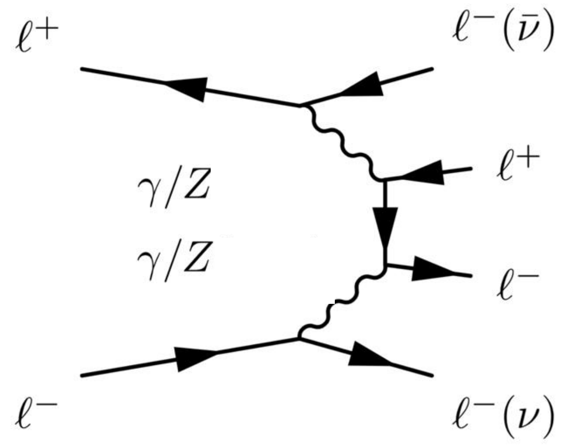


Neutral Current (NC) VBF

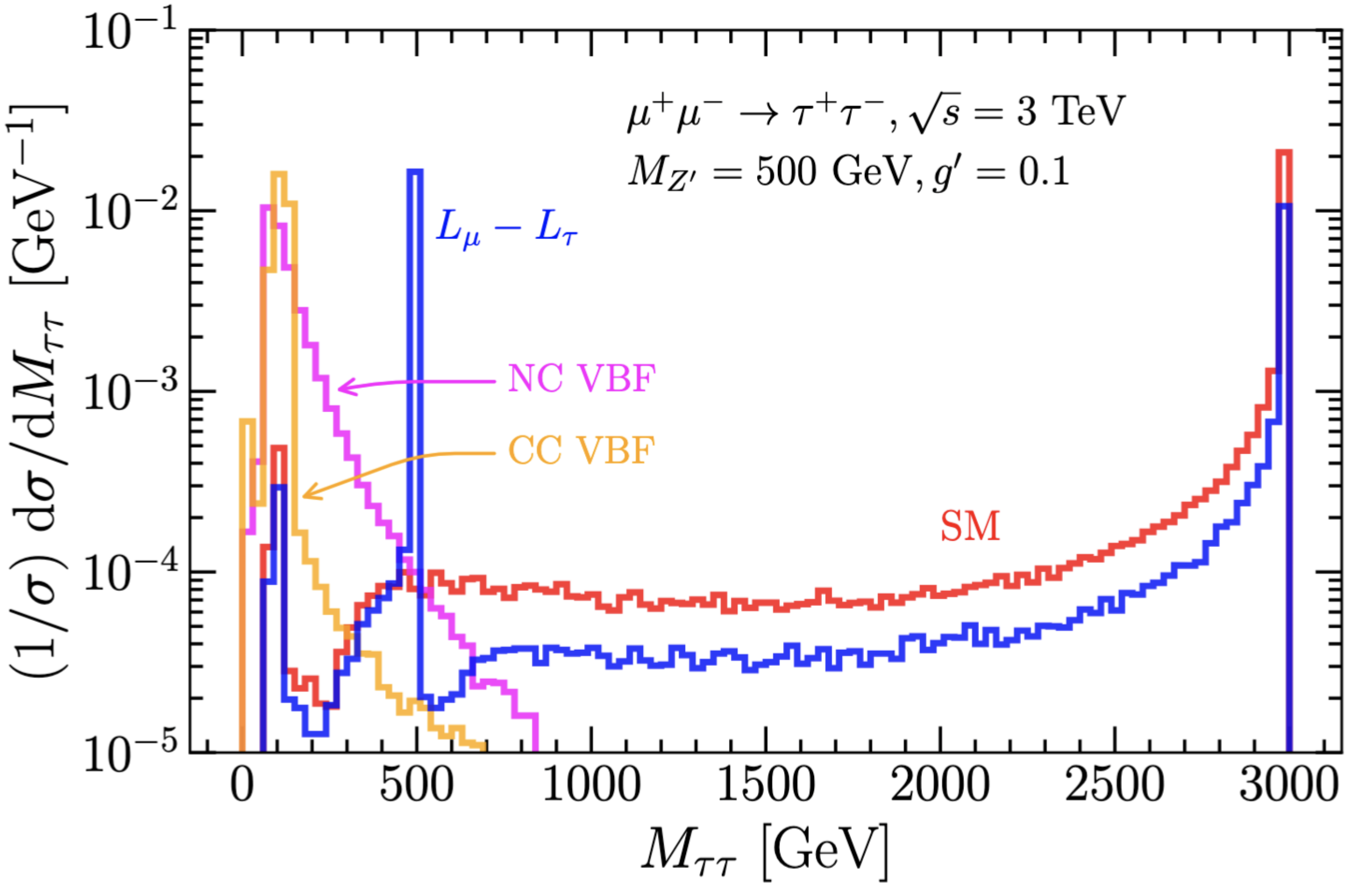
Vector Boson Fusion (VBF) Background



(CC)

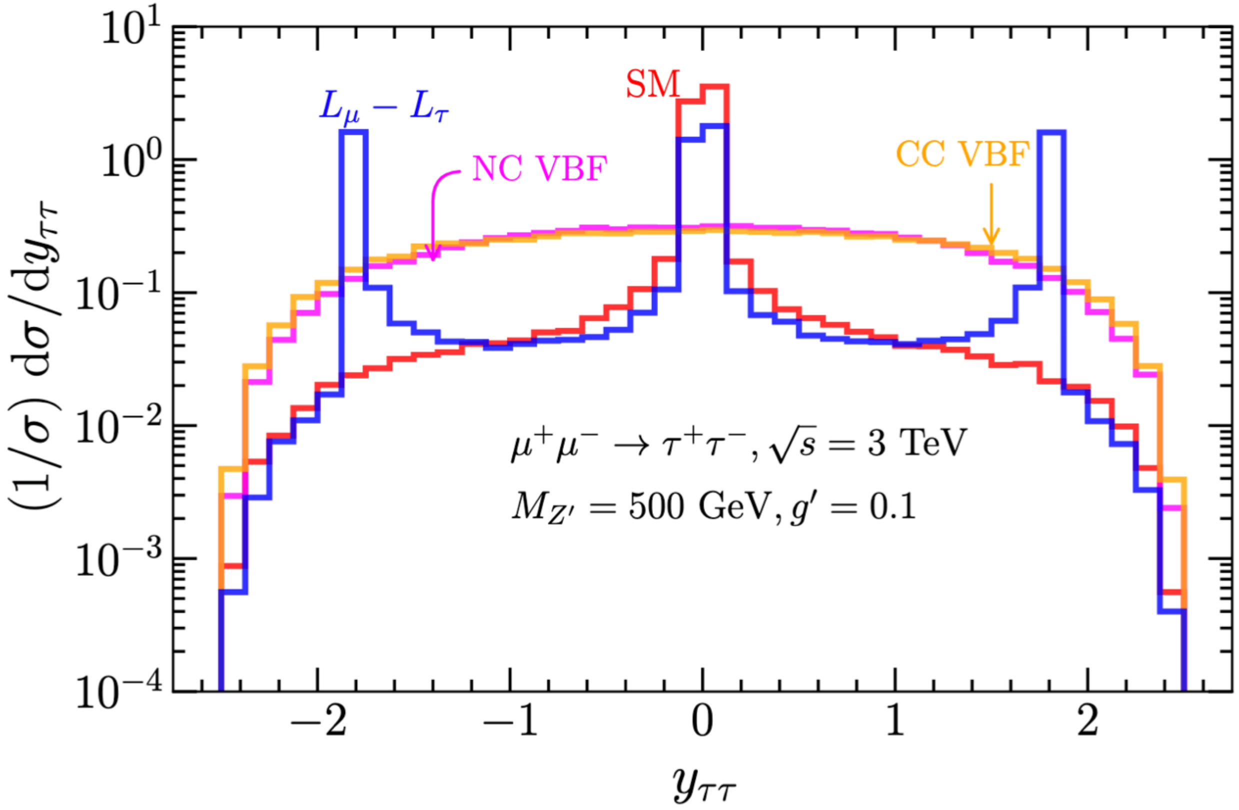


(NC)



$|M_{\ell\ell} - M_{Z'}| < 0.05 M_{Z'}$

Z' Particle On-Shell (resonance) Production



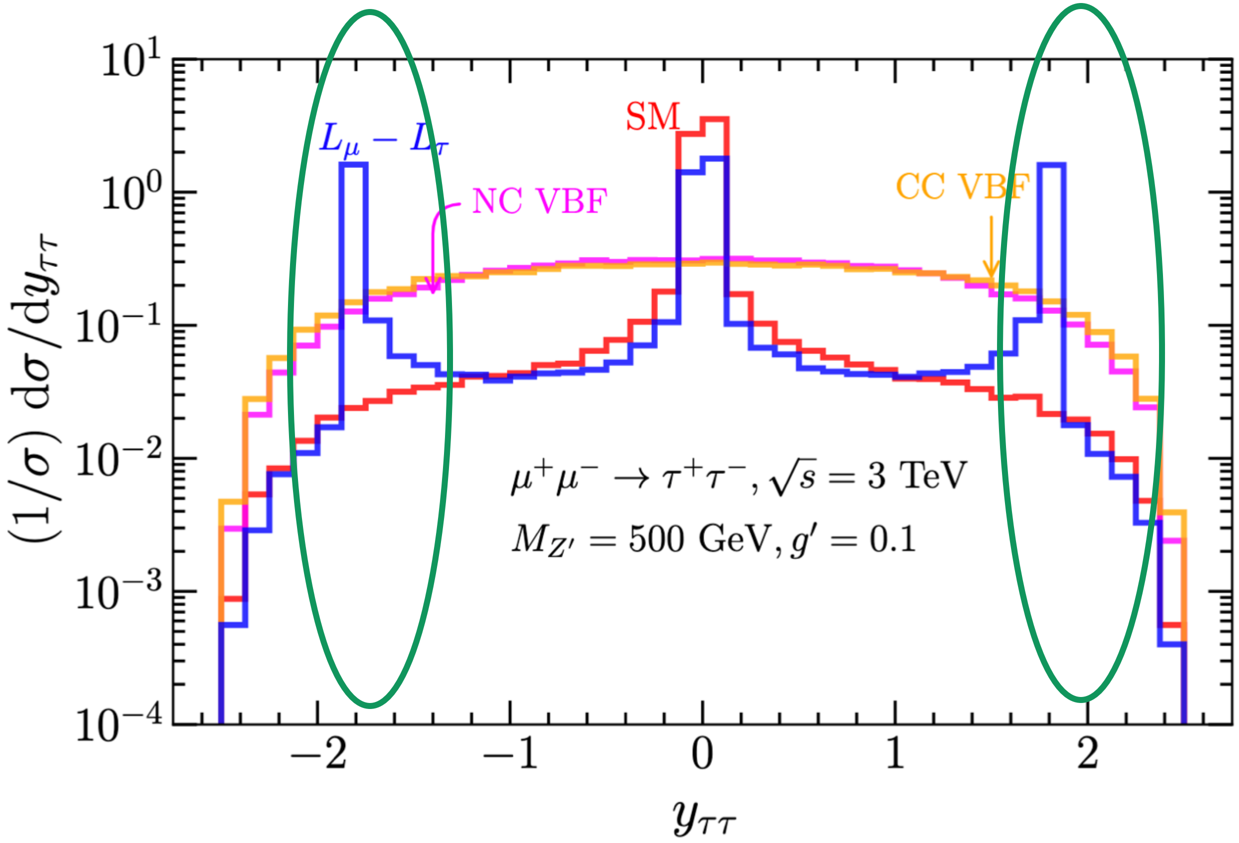
Additional Optimization Cuts:

$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

System Rapidity Cut

$$\eta = -\frac{1}{2}\ln\tan\frac{\theta}{2}$$

Z’ Particle On-Shell (resonance) Production



Additional Optimization Cuts:

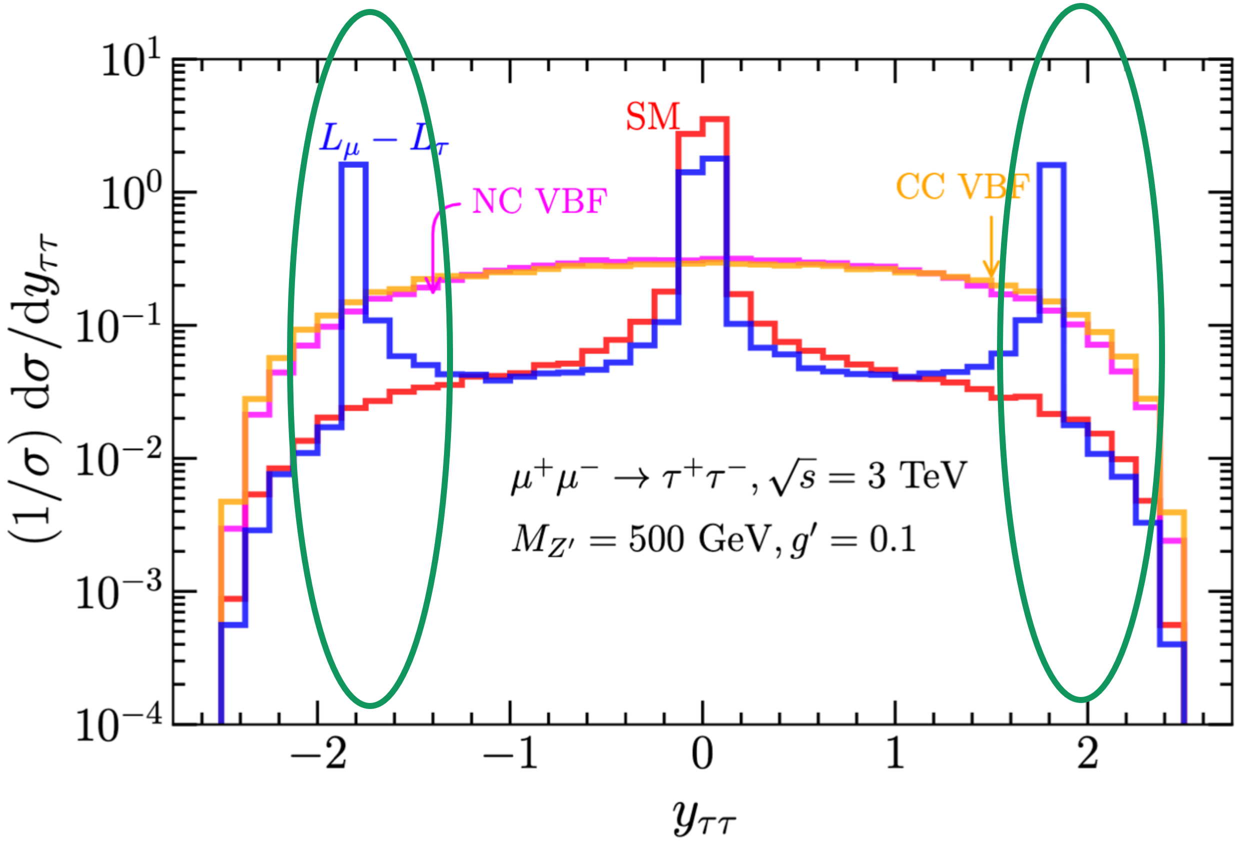
$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

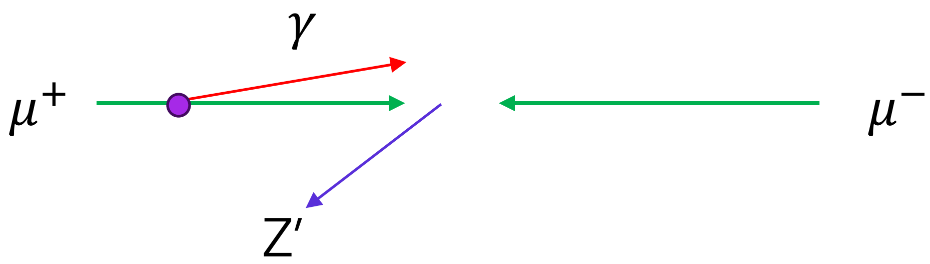
System Rapidity Cut

$$\eta = -\frac{1}{2}\ln\tan\frac{\theta}{2}$$

Z' Particle On-Shell (resonance) Production

System Rapidity Cut





$$y_{Z'} = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \boxed{\frac{1}{2}\ln\frac{M_{Z'}^2}{s}}$$

Additional Optimization Cuts:

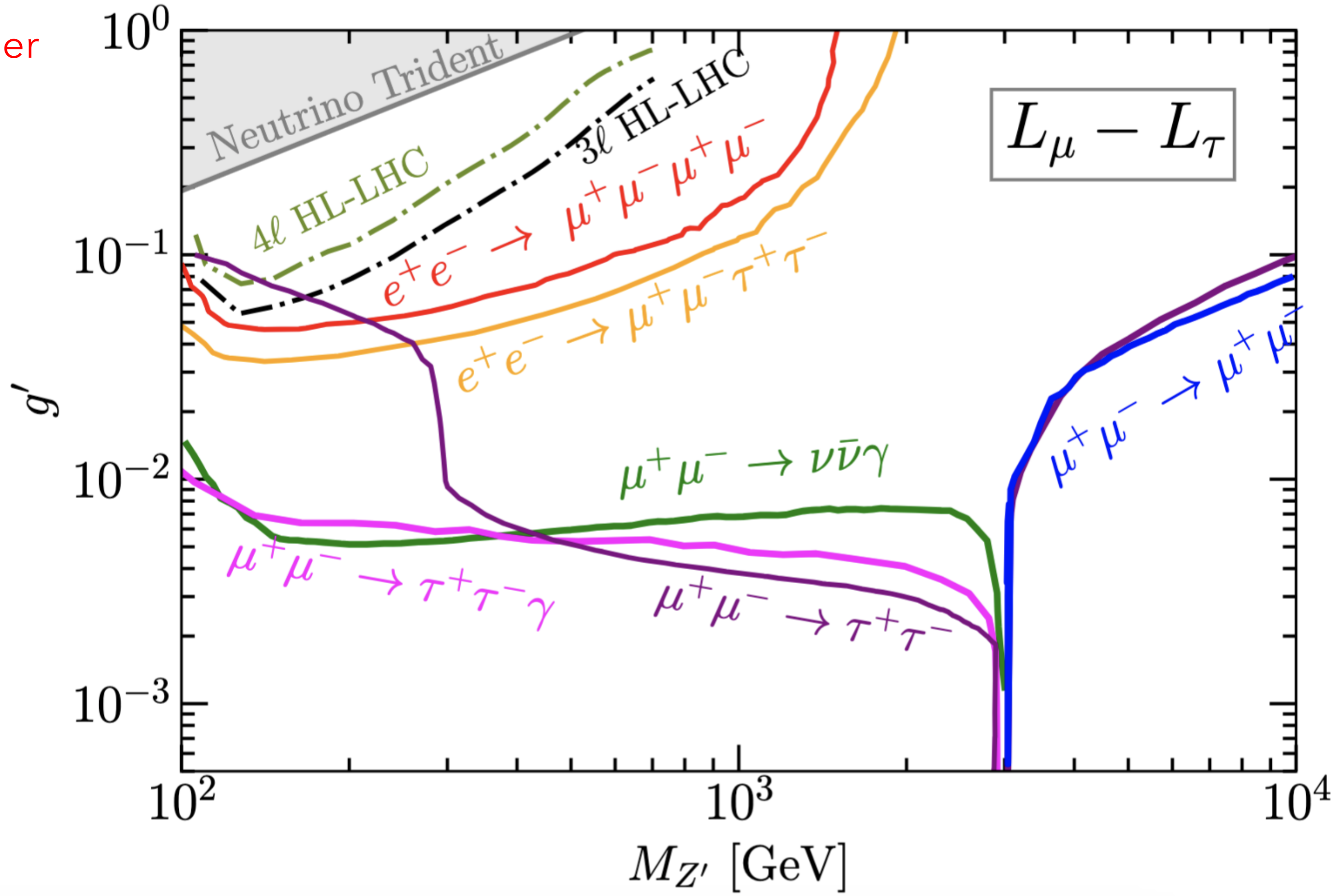
$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

Final Significance Plots

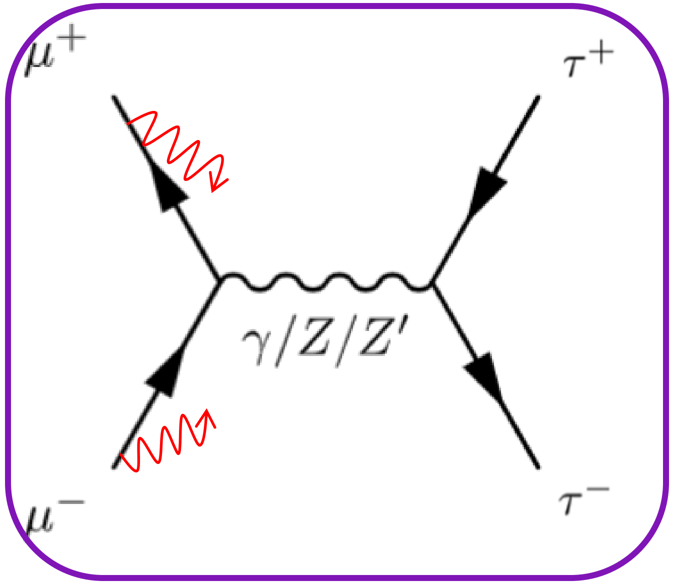
Significance Plot

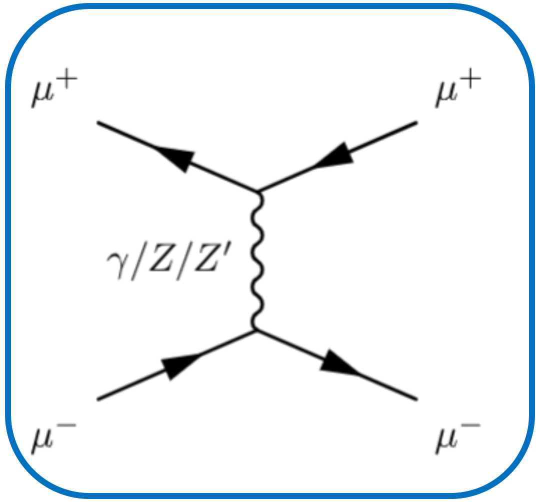
Muon Collider

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$

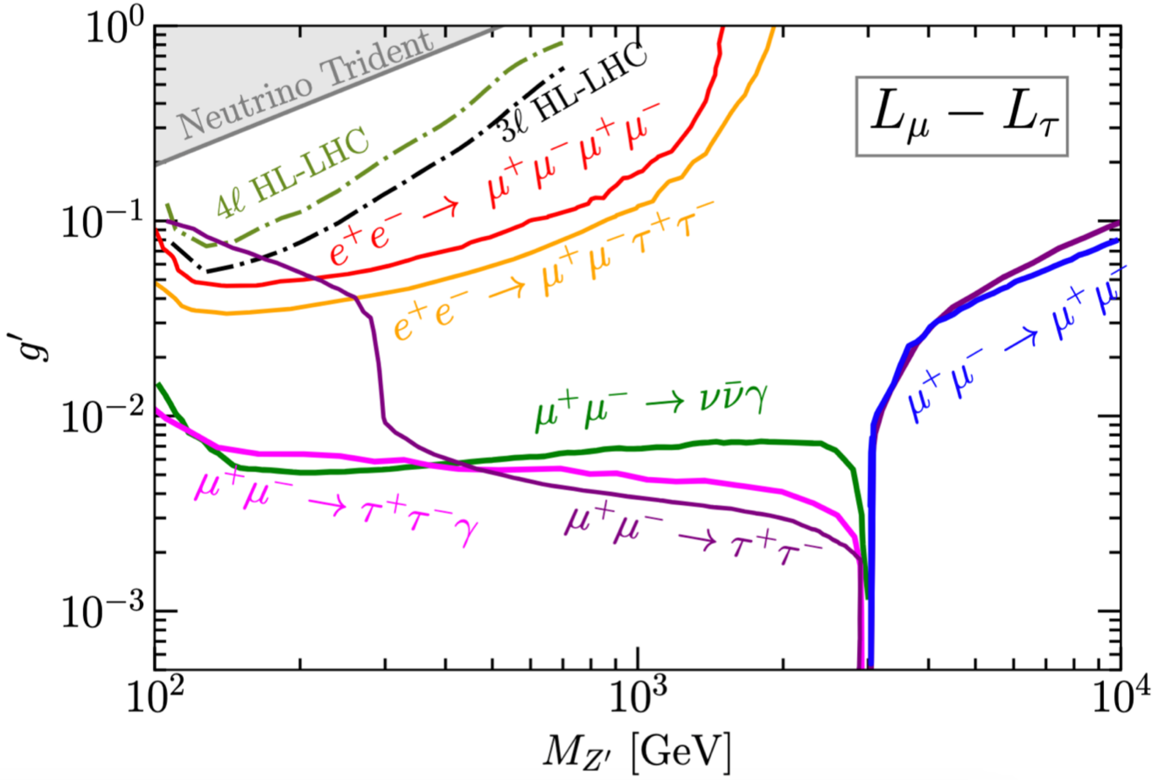


Significance Plot

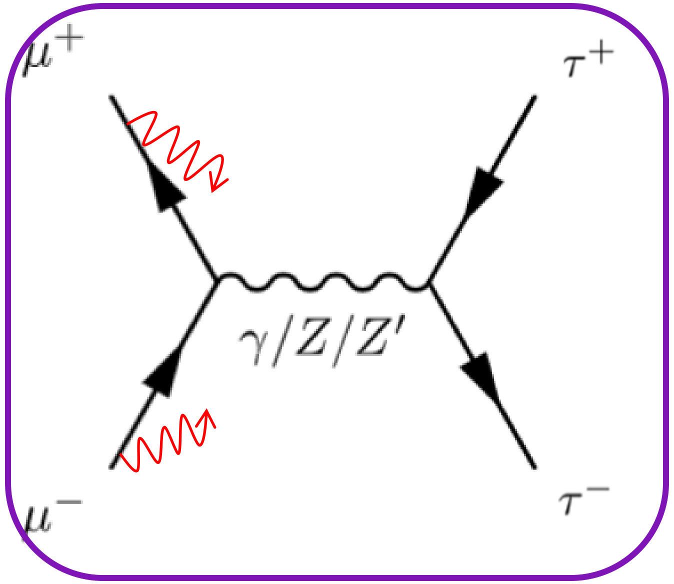


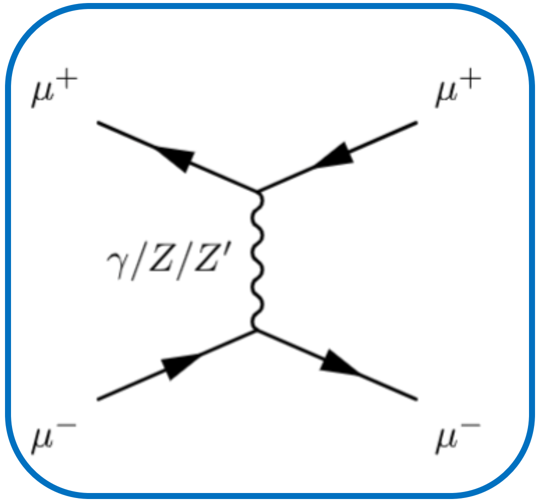


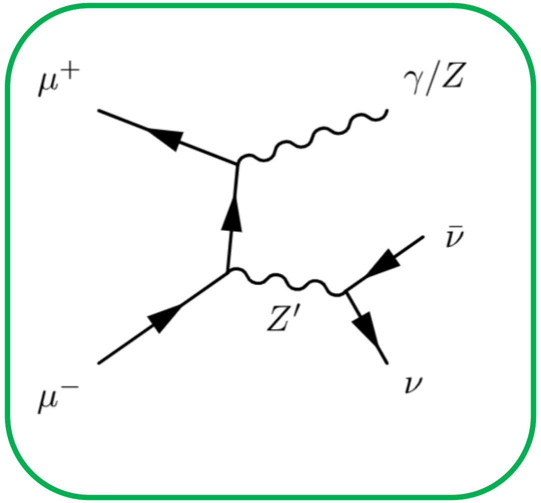
Muon Collider $\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$



Significance Plot

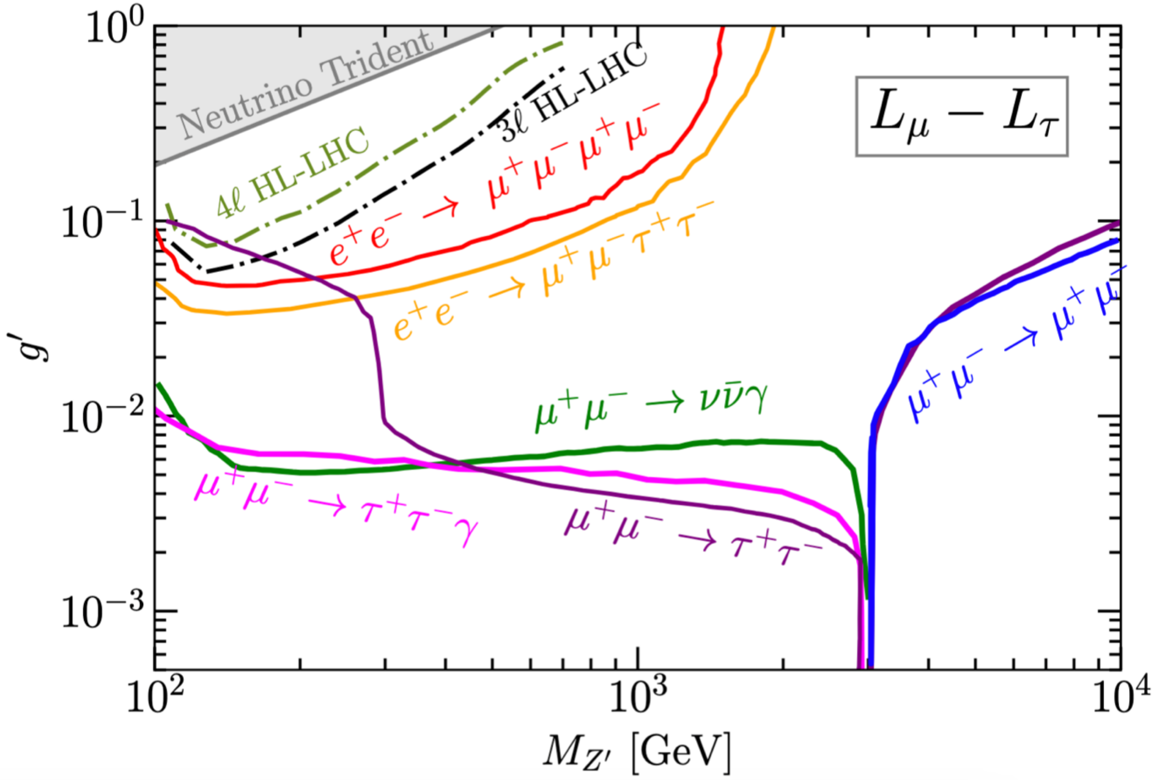




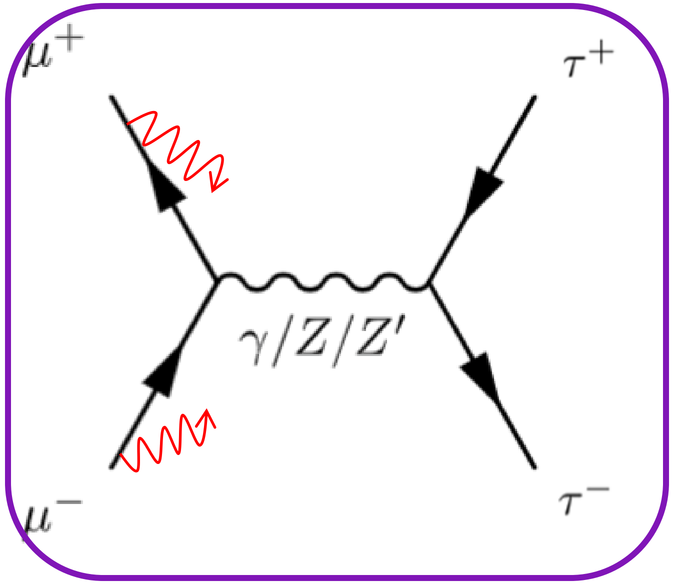


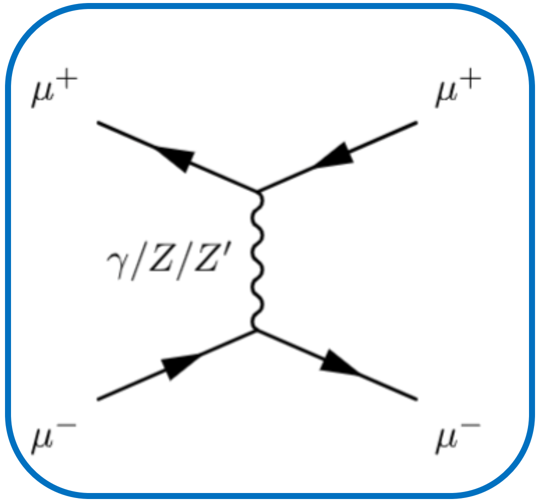
Muon Collider $\sqrt{s} = 3$ TeV

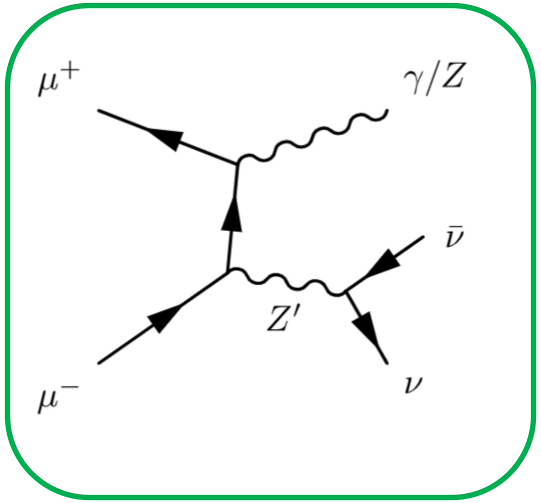
$\mathcal{L} = 1\ ab^{-1}$

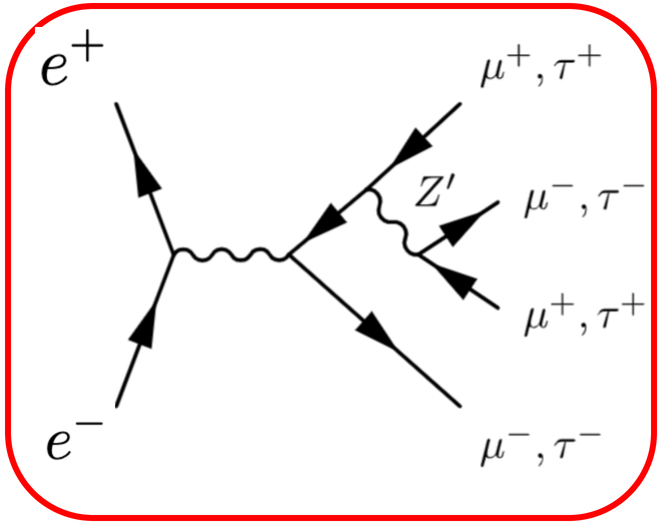


Significance Plot

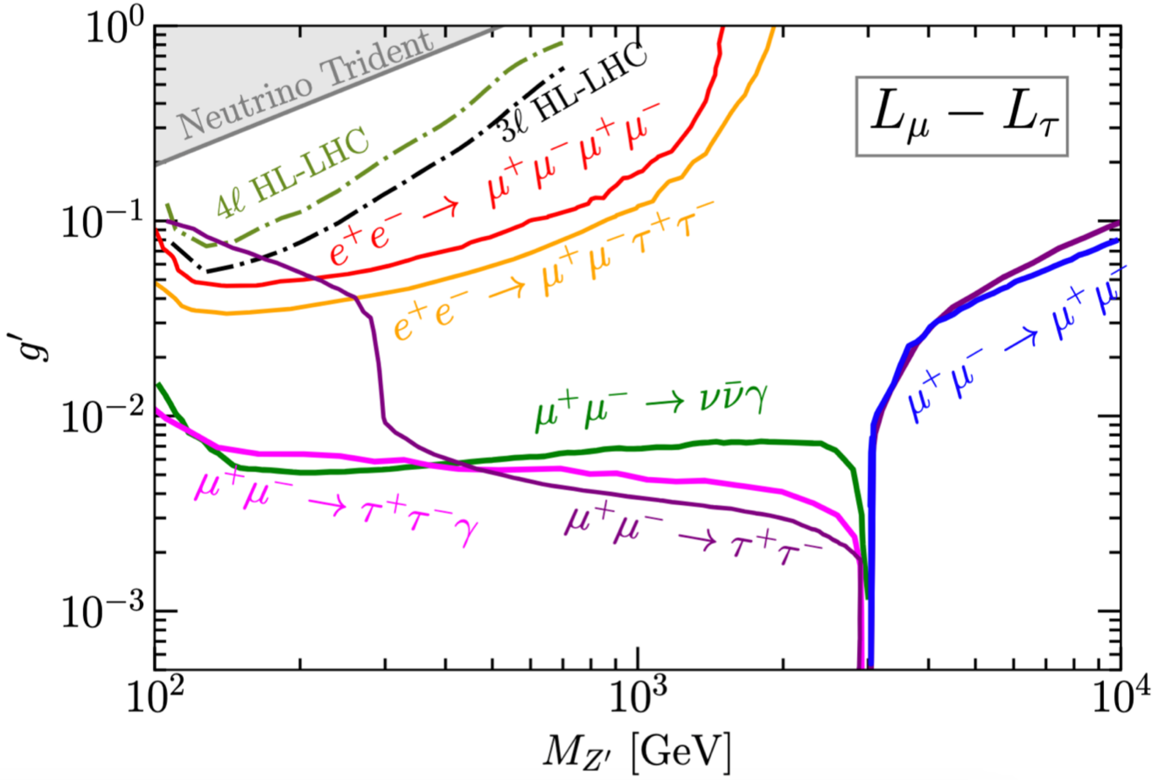








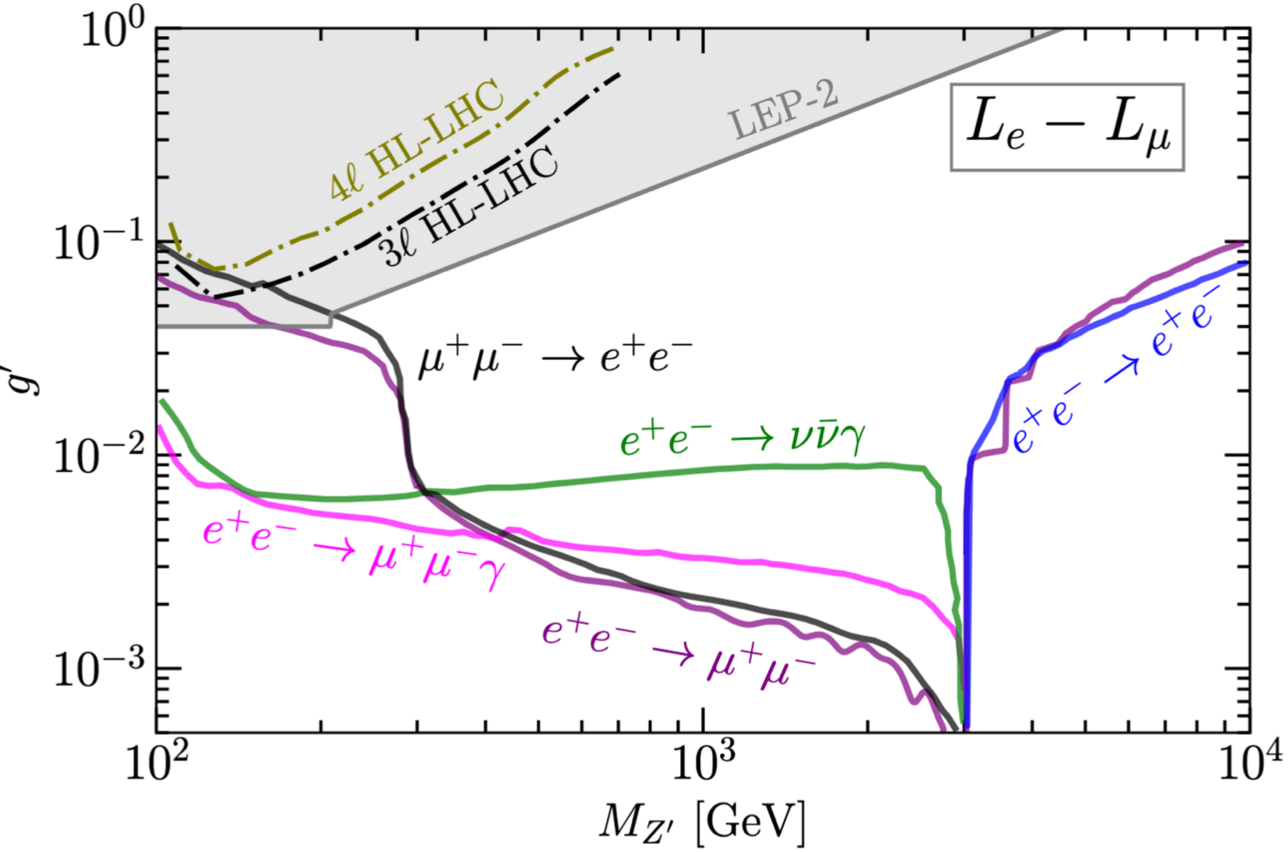
Muon Collider $\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\ ab^{-1}$

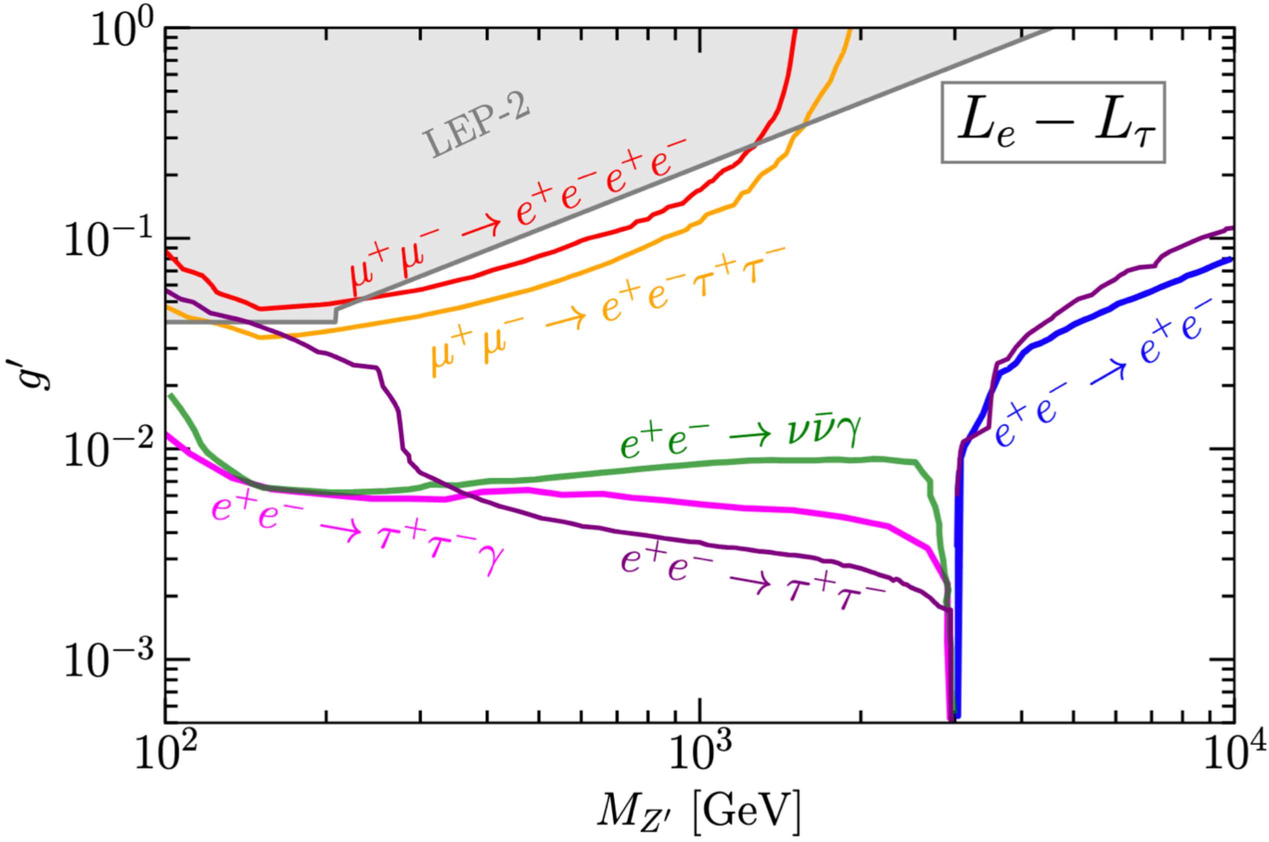


Significance Plots

Electron Collider

$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1\, ab^{-1}$





Gravitatioanal Waves Part

New Scalar Field Effective Potential

Φ

$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi)$$

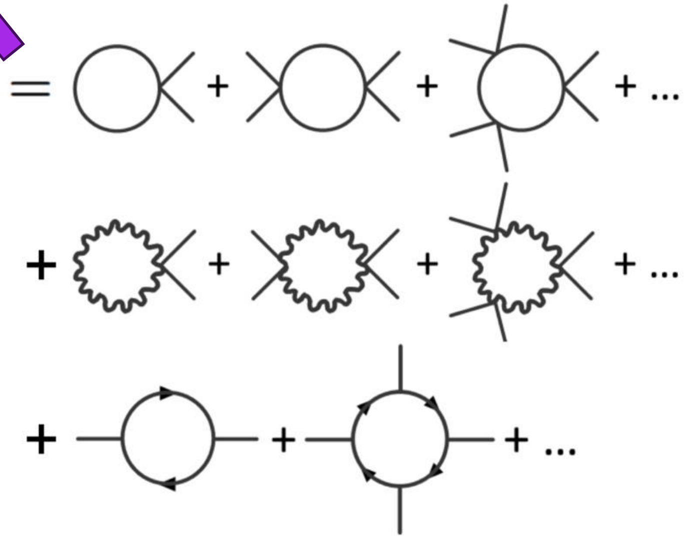
$$\frac{1}{4}\lambda\phi^4$$

New Scalar Field Effective Potential

Φ

$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi)$$

$$\frac{1}{4}\lambda\phi^4$$



scalar

boson

Fermion

Image credit: Arthur Wu

New Scalar Field Effective Potential

Φ

$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi)$$

$$\frac{1}{4}\lambda\phi^4$$

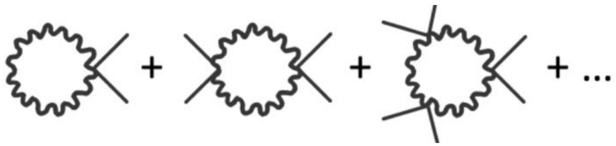


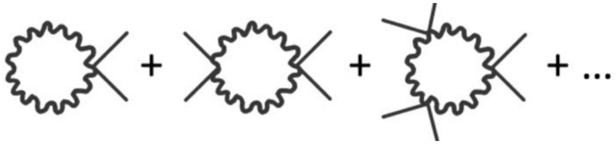
Image credit: Arthur Wu

New Scalar Field Effective Potential

Φ

$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi) + V_T(\phi, T)$$

$$\frac{1}{4}\lambda\phi^4$$

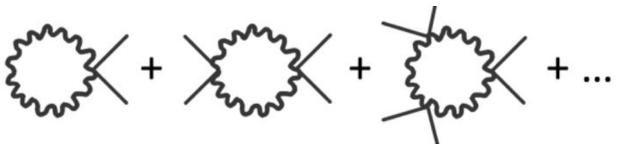


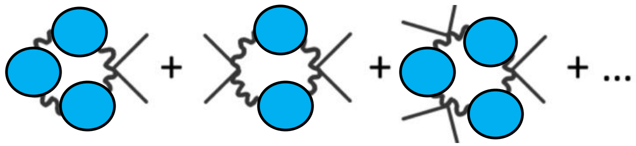
New Scalar Field Effective Potential

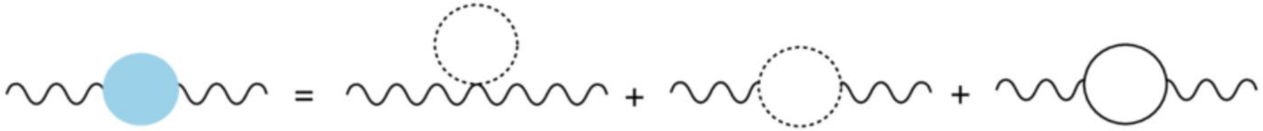
Φ

$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi) + V_T(\phi, T) + V_{\text{daisy}}(\phi, T)$$

$$\frac{1}{4}\lambda\phi^4$$

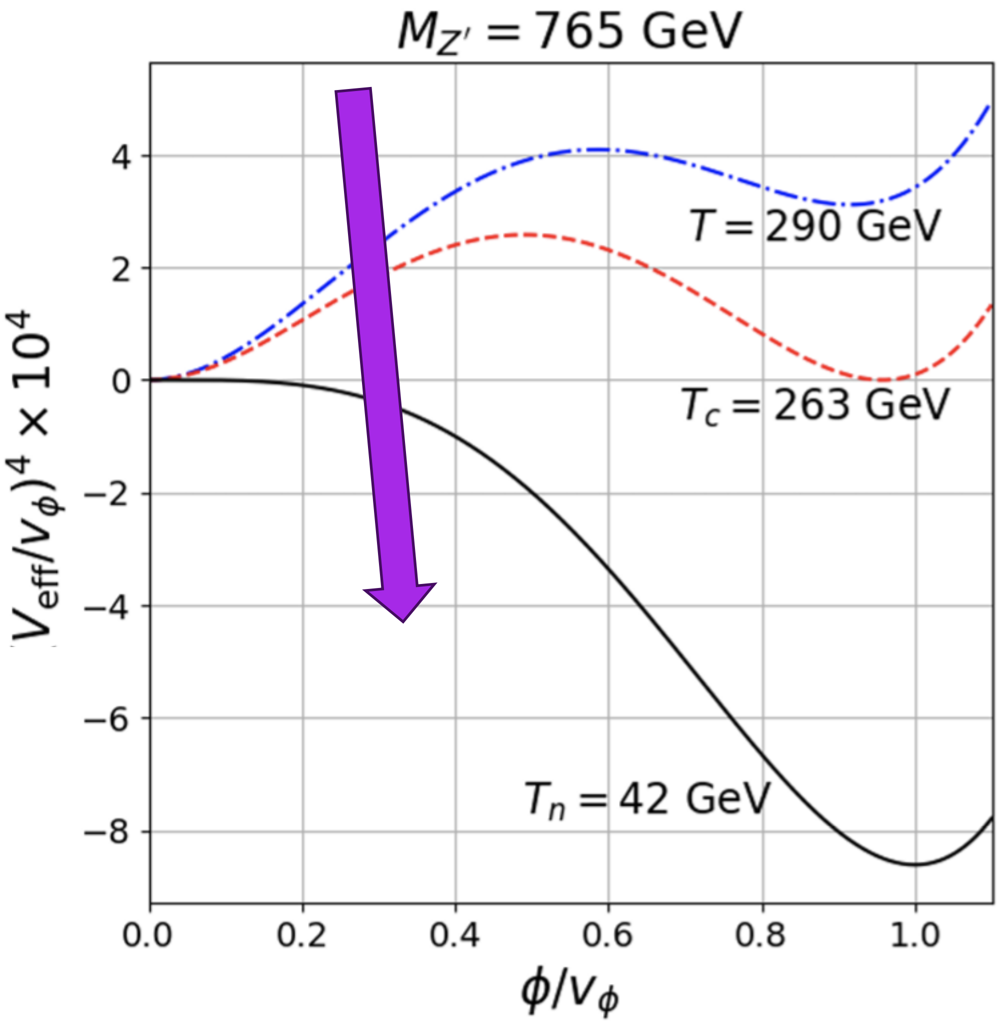






arXiv:2009.02050

New Scalar Field Effective Potential



First Order Phase Transition

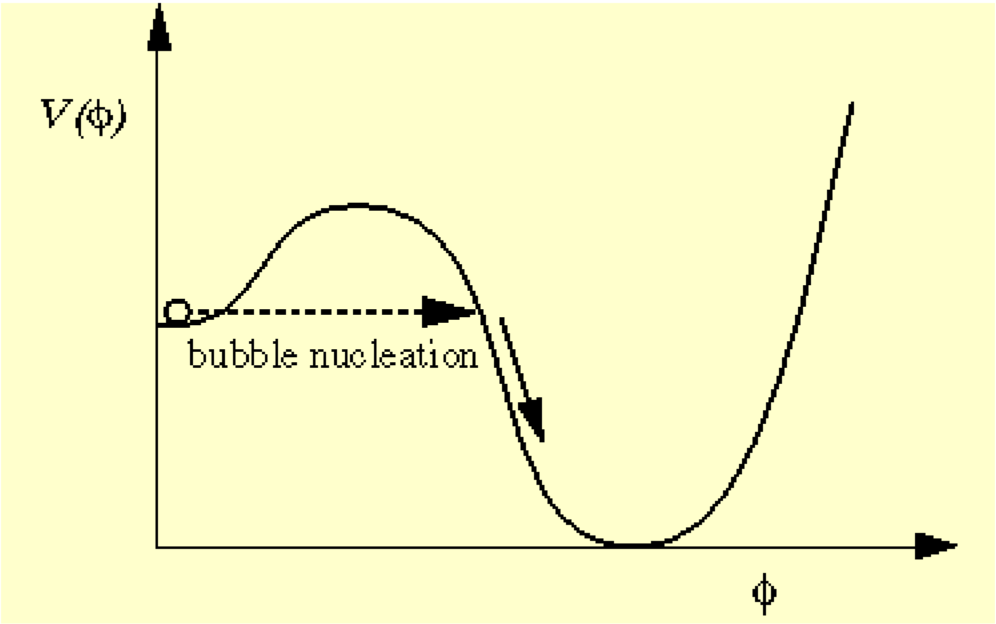
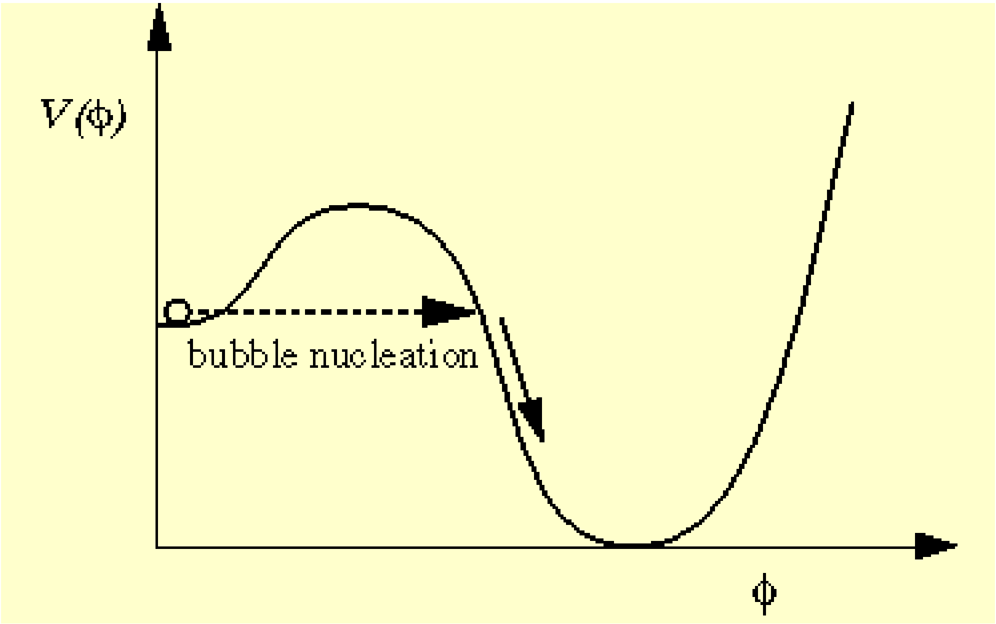


Image credit: Cambridge U

First Order Phase Transition



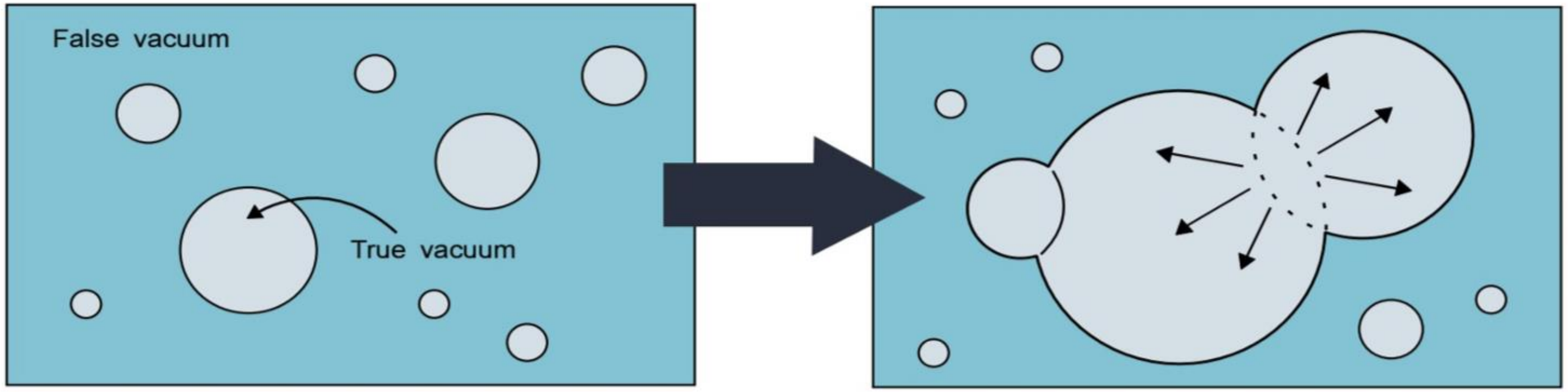
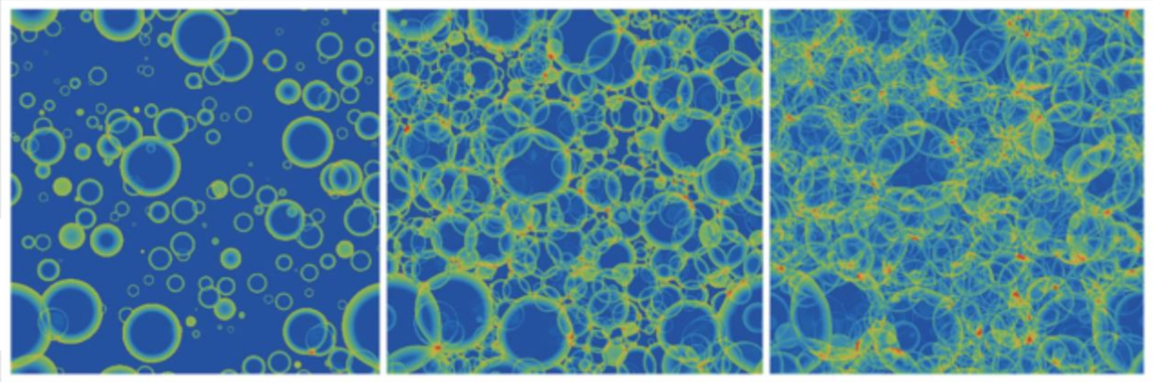


Image credit:
Giulio Barni

First Order Phase Transition

First Order Phase Transition



Bubble nucleation Simulation of Higgs-bubble nucleation and expansion history during a first-order electroweak phase transition. Source: *JCAP* **04** 014

Bubble nucleation rate: $\Gamma(T) = [A(T)]^4 \exp[-S(T)]$

Nucleation Temperature when: $\left.\frac{\Gamma(T)}{H(T)^4}\right|_{T=T_n} = 1$

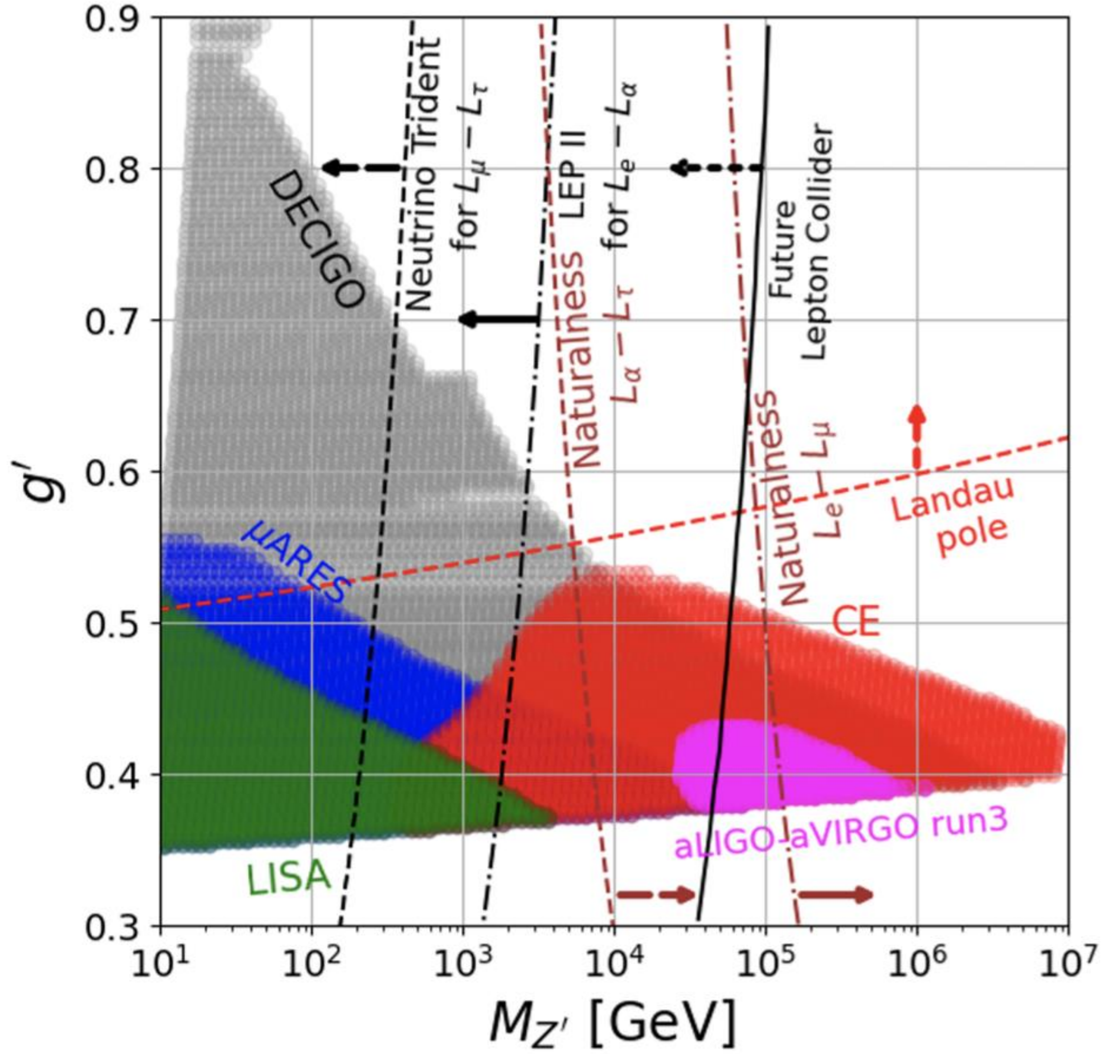
Vacuum energy density: $\alpha = \frac{1}{\rho_{\rm rad}} \left(-1 + T \frac{\mathrm{d}}{\mathrm{d}T} \right) \Delta V_{\rm min} \bigg|_{T=T_*}$ (Transition temperature)

Inverse timescale: $\frac{\beta}{H_*} = -\frac{T}{\Gamma} \frac{\mathrm{d}\Gamma}{\mathrm{d}T} \bigg|_{T=T_*}$

Bubble wall velocity: v_w

Gravitational Waves: $h^2 \Omega_{\rm GW}(f) \simeq h^2 \Omega_b(f) + h^2 \Omega_s(f) + h^2 \Omega_t(f)$

Gravitational Waves Constraints



$$M_{Z'} = 2g'v_\Phi$$

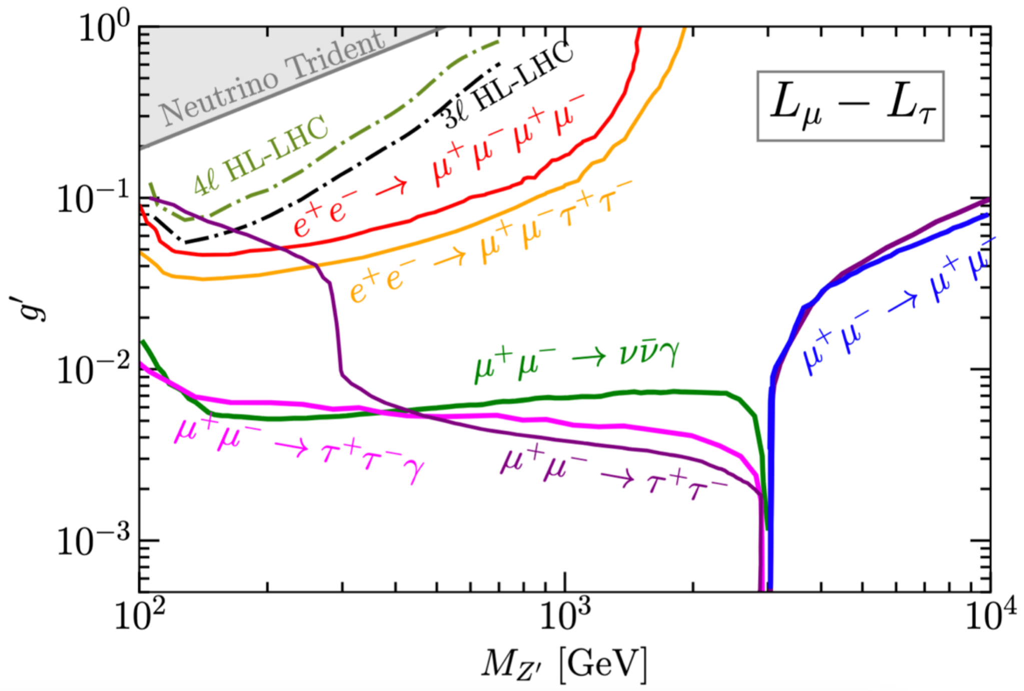
Summary

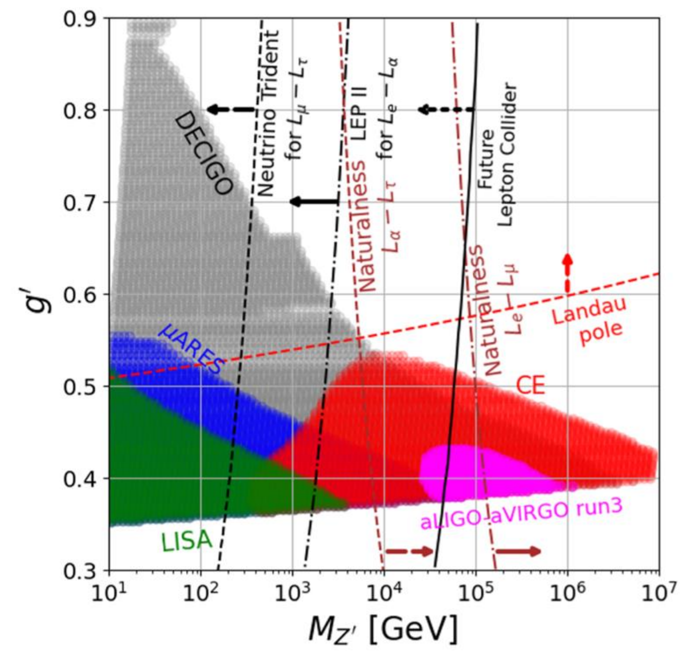
1. $SU(2)_L \times U(1)_Y \times U(1)'$

   New particles:
   gauge boson Z' and singlet scalar ϕ

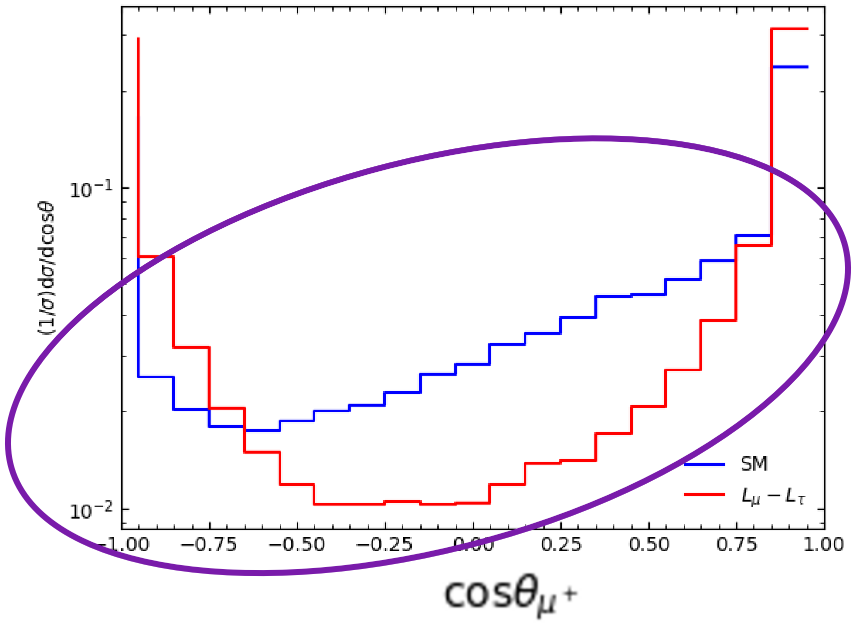
2. adding system rapidity cut
   enhanced the sensitivity

3. Gravitational Waves can be
   a complementary to the collider constrainsts





$\mu^+\mu^- \to \tau^+\tau^-$ with ISR



$\sqrt{s} = 3$ TeV
$M_{Z'} = 500$ GeV
g′=0.2

For $M_{Z'}$ 3 TeV to 10 TeV

$$\frac{S}{\sqrt{B}} = \frac{(\sigma_{Lmt} - \sigma_{SM})L}{\sqrt{\sigma_{SM}L}}$$

Chi square:

$$\chi^2 = \sum_i \frac{(N_i^{BSM} - \tilde{N}_i^{SM})^2}{\tilde{N}_i^{SM} + \epsilon^2 \tilde{N}_i^{SM2}}$$

Model $L_\mu - L_\tau$ Back Up

$$\mathscr{L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y \,.$$

1 $$\mathscr{L}_{YM}^{\text{Abel}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu},$$

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \,,$$
$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu \,.$$

2 $$\mathscr{L}_f = \sum_{k=1}^{3}\Big(i\overline{q_{kL}}\gamma_\mu D^\mu q_{kL} + i\overline{u_{kR}}\gamma_\mu D^\mu u_{kR} + i\overline{d_{kR}}\gamma_\mu D^\mu d_{kR} + $$
$$+ i\overline{l_{kL}}\gamma_\mu D^\mu l_{kL} + i\overline{e_{kR}}\gamma_\mu D^\mu e_{kR} + i\overline{\nu_{kR}}\gamma_\mu D^\mu \nu_{kR}\Big)\,,$$

$$D^\mu = \partial_\mu + ig_s T^\alpha G^\alpha_\mu + igT^a W^a_\mu + ig_1 Y B_\mu + ig'_1 Y_{L_\mu - L_\tau} B'_\mu$$

3 $$\mathscr{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger D_\mu \chi - V(H,\chi)\,,$$

$$V(H,\chi) = m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2\,,$$

4 $$\mathscr{L}_Y = -y^d_{jk}\overline{q_{jL}}d_{kR}H - y^u_{jk}\overline{q_{jL}}u_{kR}\widetilde{H} - y^e_{jk}\overline{l_{jL}}e_{kR}H$$
$$-y^\nu_{jk}\overline{l_{jL}}\nu_{kR}\widetilde{H} - y^M_{jk}\overline{(\nu_R)^c_j}\nu_{kR}\chi + \text{h.c.}\,,$$

Anomaly Cancellation

For extra $U(1)'$ model, there are six anomaly-cancellation condition:

(1) $SU(3)_C^2 \times U(1)'$, implies $Tr[\{\mathcal{T}^i, \mathcal{T}^j\}Y'] = 0$, which leads to $\sum_{colortriplets,i} Y_i' = 0$,

(2) $SU(2)_L^2 \times U(1)'$, implies $Tr[\{T^i, T^j\}Y'] = 0$, which leads to $\sum_{isodoublets,i} Y_i' = 0$,

(3)$U(1)_Y^2 \times U(1)'$, implies $Tr[Y^2 Y'] = 0$, which leads to $\sum_i Y_i^2 Y_i' = 0$,

(4)$U(1)_Y \times U(1)'^2$, implies $Tr[YY'^2] = 0$, which leads to $\sum_i Y_i Y_i'^2 = 0$,

(5)$U(1)'^3$, implies $Tr[Y'^3] = 0$, which leads to $\sum_i Y_i'^3 = 0$,

(6)Gauge gravity, implies $Tr[Y'] = 0$, which leads to $\sum_i Y_i' = 0$

$$
\begin{aligned}
& Y'_{eR} && +Y'_{\mu R} + Y'_{\tau R} + 2(Y'_{eL} + Y'_{\mu L} + Y'_{\tau L}) \\
+3*2(& Y'_{uL} && +Y'_{cL} + Y'_{tL}) + 3*2(Y'_{uR} + Y'_{cR} + Y'_{tR}) = 0
\end{aligned}
$$

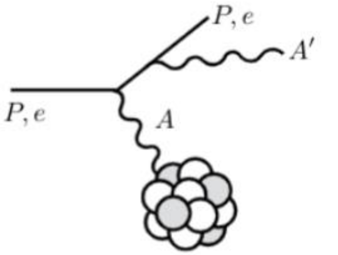
Current Constraints

[M. Bauer, P. Foldenauer, J. Jaeckel(2018)]

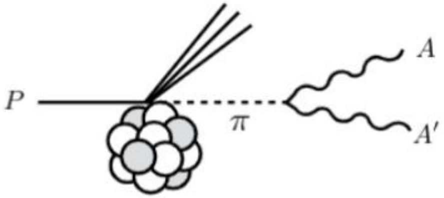
Mass region: MeV-100 GeV

1.Beam dump experiments
& fixed target experiments

(SLAC E137, Fermilab E774, Orsay;
SHiP…)



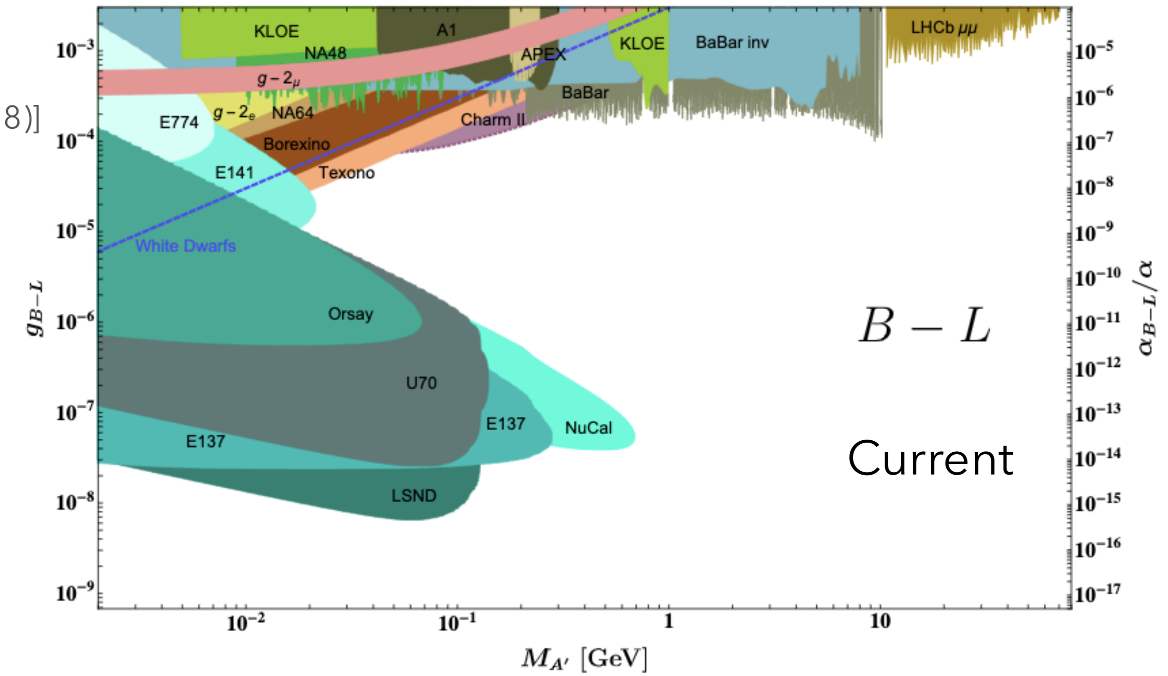
Bremsstrahlung

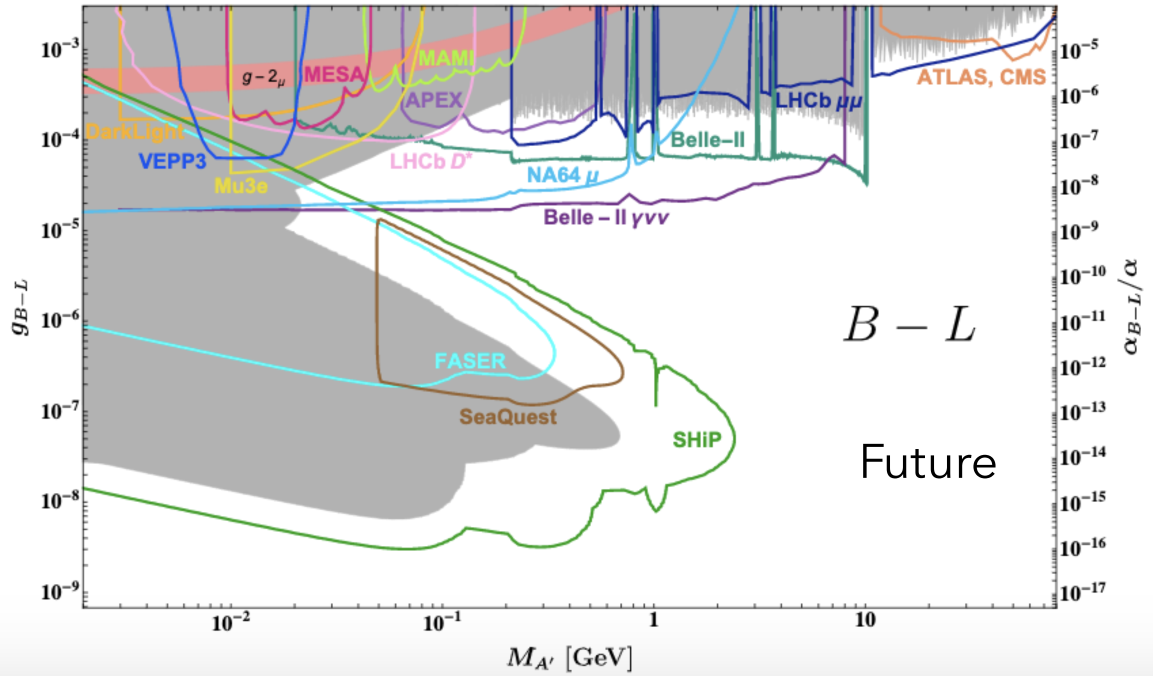


meson production

2.Neutrino Experiments

(COHERENT, Charm-II, Texono…)





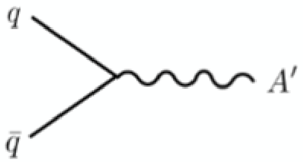
Current Constraints

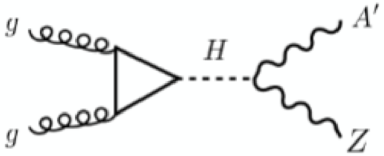
[M. Bauer, P. Foldenauer, J. Jaeckel(2018)]

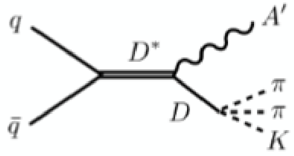
Mass region: MeV-100 GeV

3.Collider Experiments

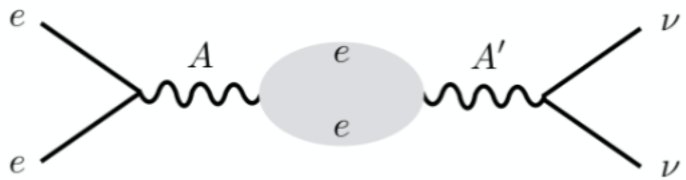
(ATLAS, CMS, LHCb, BaBar, KLOE…)

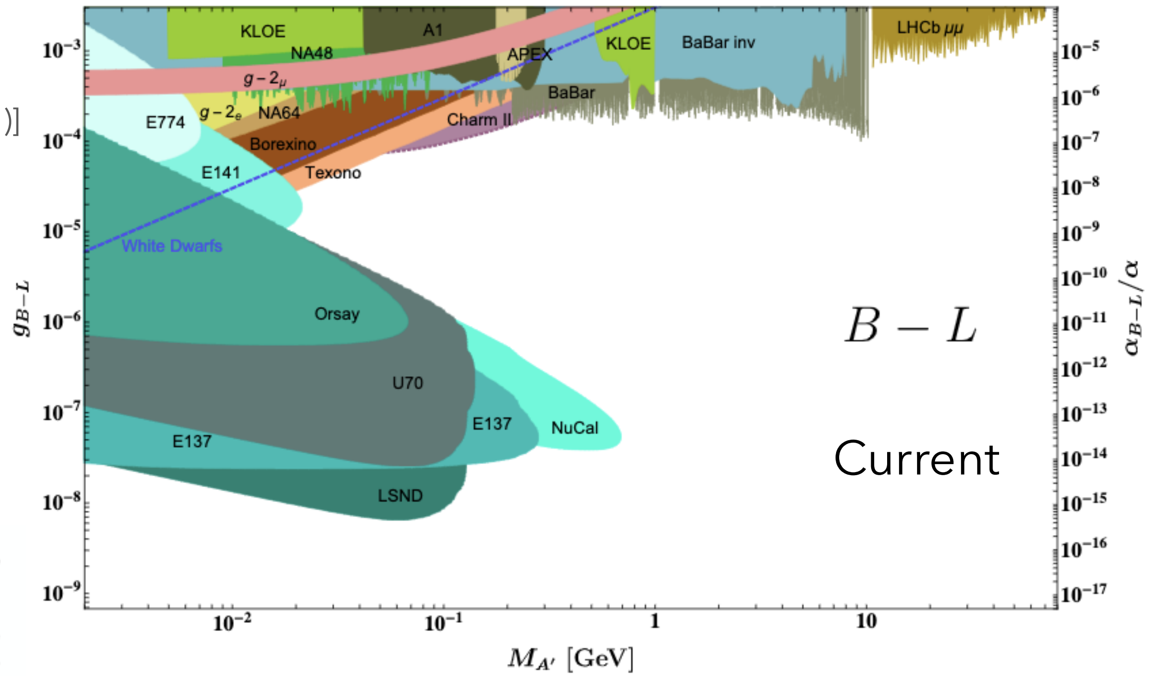


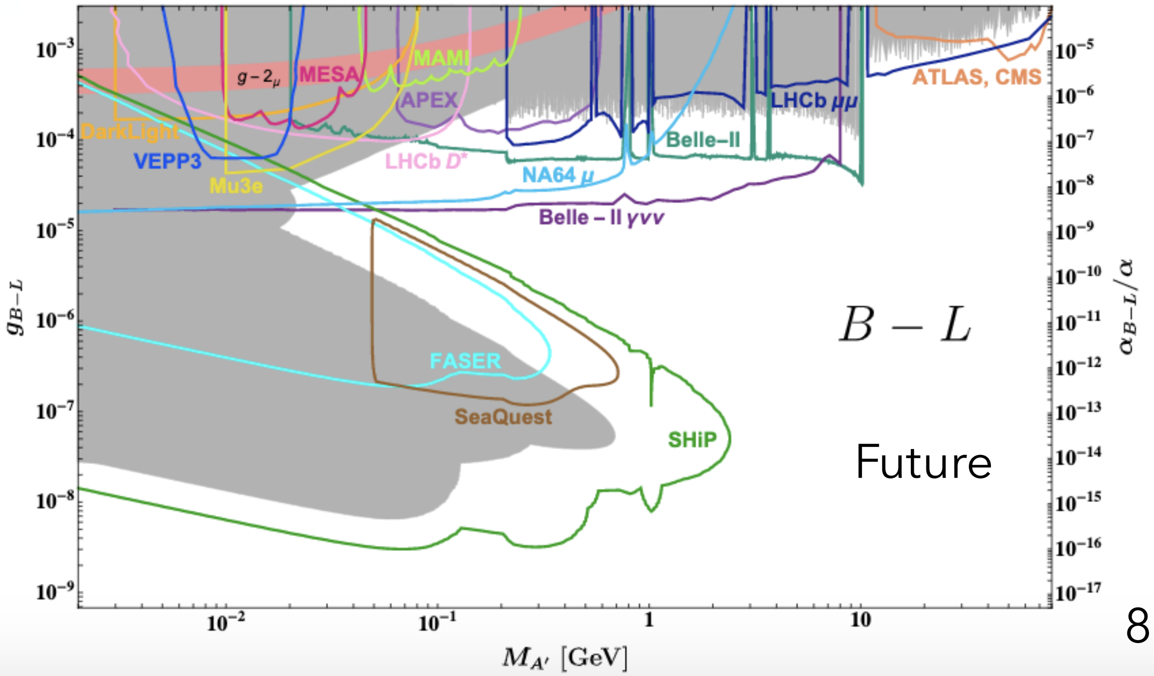




4. White Dwarf Cooling

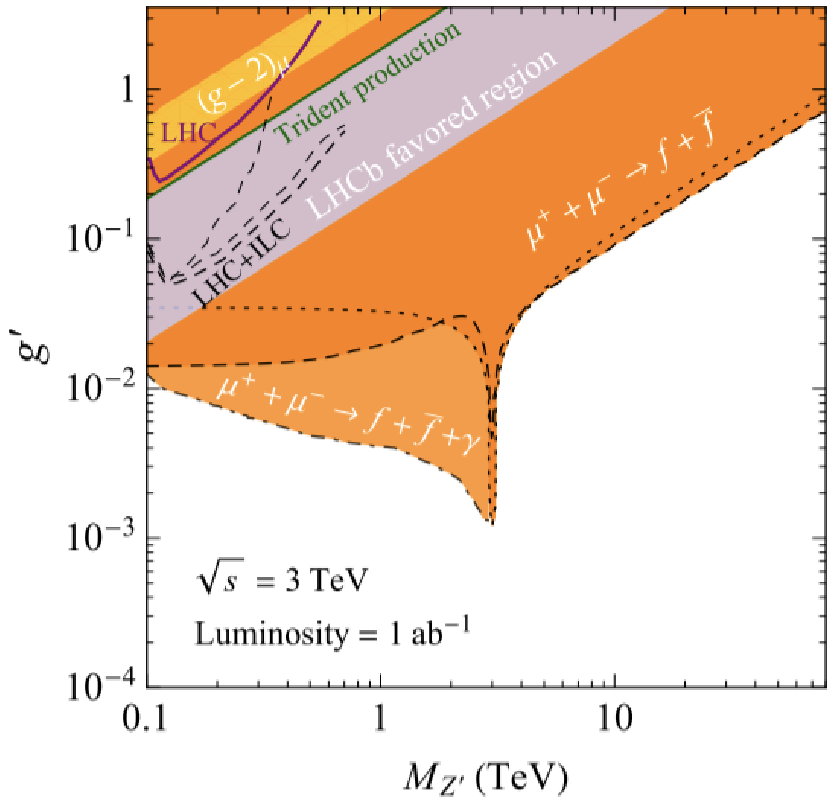






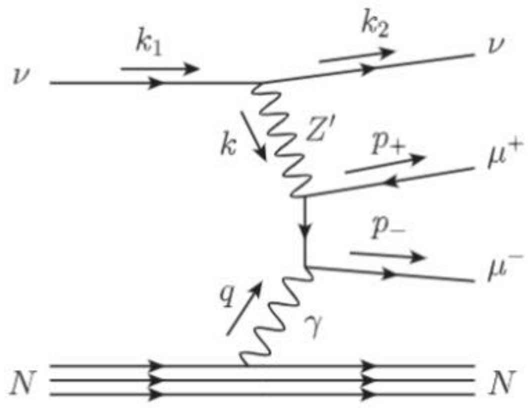
Current Constraints

Mass region: 0.1 TeV to 100 TeV



[G. Huang, F.S. Queiroz, W. Rodejohann(2021)]]

Neutrino Trident Exeperiment:



$$\sigma_{CCFR}/\sigma_{SM} = 0.82 \pm 0.28$$

$$\frac{\sigma_{SM+Z'}}{\sigma_{SM}} = \frac{1 + (1 + 4s_W^2 + 2v^2 q_l^2 (g')^2/M_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$

$$M_{Z'} > 540 \text{ GeV} \times g'$$

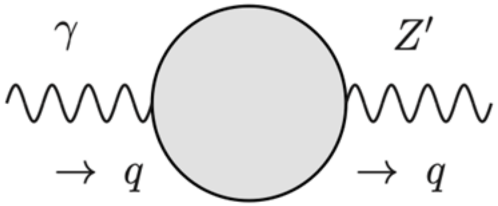
should consider VBF background

Z-Z′ Mixing

Mixing term

$$\mathcal{L}_{\rm mix} = -\epsilon Z'^{\mu\nu} B_{\mu\nu} + \delta M^2 Z'^{\mu} Z_{\mu}$$

$\Pi(q^2) \equiv$



$$= \frac{8eg'}{16\pi^2} \int_0^1 dx\; x(1-x) \log\left[\frac{m_{\ell_\beta}^2 - x(1-x)q^2}{m_{\ell_\alpha}^2 - x(1-x)q^2}\right]$$

Z′ Particle Width

No RH LH difference

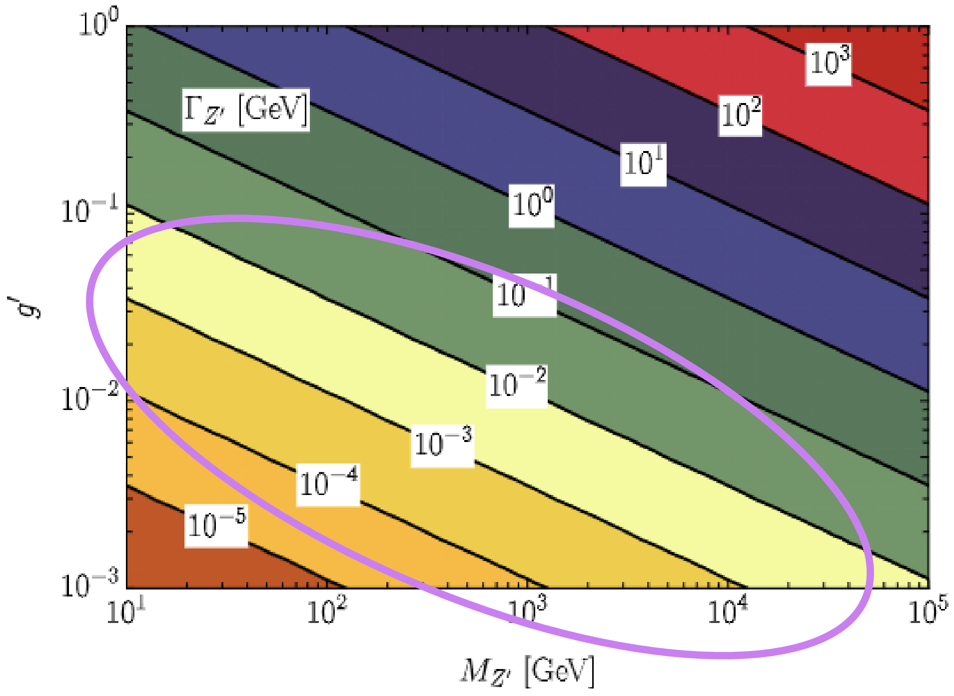
Width:

$$\mathcal{M} = -g' \epsilon^{\mu} \bar{u}(p_1) \gamma_{\mu} v(p_2)$$

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

$$\Gamma(Z' \to l\bar{l}) = 2\Gamma(Z' \to \nu\bar{\nu})$$

$$\Gamma_{tot} = \frac{(2N_l + N_\nu) g'^2}{24\pi} M_{Z'} = \frac{6g'^2}{24\pi} M_{Z'}$$



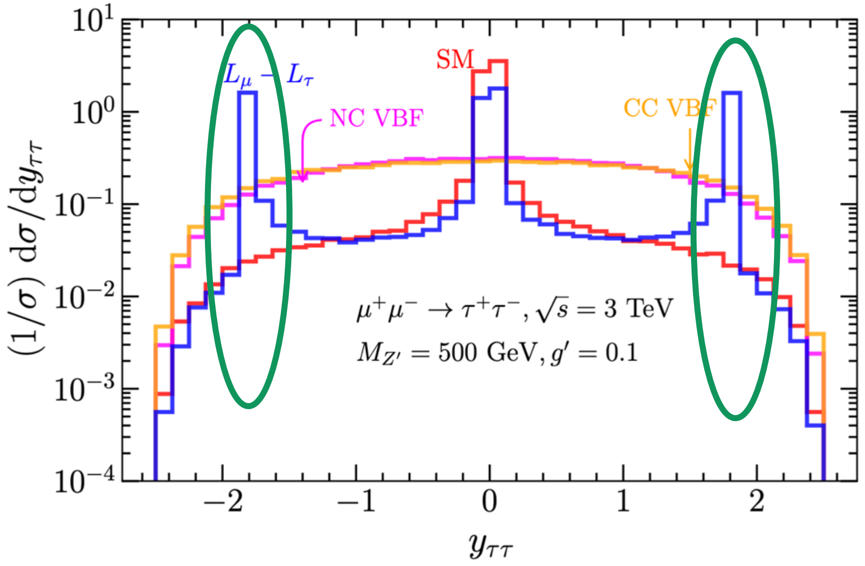
Ignore lepton masses

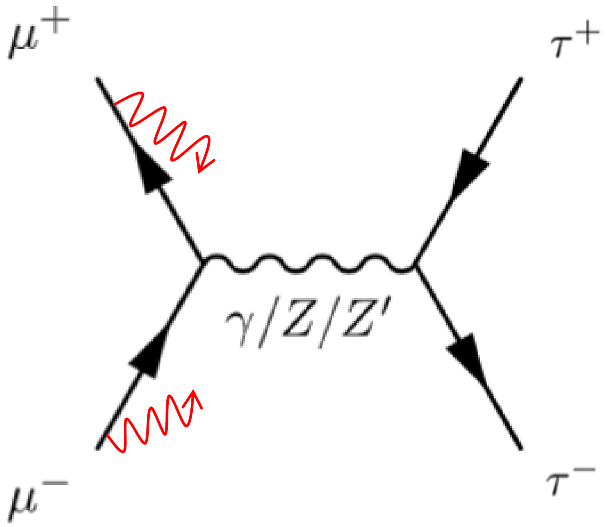
$$c\tau = \frac{c}{\Gamma(Z')} = 2.48 \times 10^{-4}\ \mu m \left(\frac{10^{-3}}{g'}\right)^2 \left(\frac{10\ \text{GeV}}{M_{Z'}}\right)$$

Prompt decay

On-Shell Z' Particle Production

System Rapidity Cut





(momentum conservation)

$$P_{Z'} = P_{\mu^+} + P_{\mu^-} = \left(\frac{1}{2}\sqrt{s} - E_\gamma, \frac{1}{2}\sqrt{s} - E_\gamma\right) + \left(\frac{1}{2}\sqrt{s}, -\frac{1}{2}\sqrt{s}\right) = (\sqrt{s} - E_\gamma, -E_\gamma)$$

$$M_{Z'}^2 = P_{Z'}^2 = (\sqrt{s} - E_\gamma)^2 - E_\gamma^2 = s - 2\sqrt{s}E_\gamma$$

(the energy-momentum relation)

$$E_\gamma = (s - M_{Z'}^2)/2\sqrt{s}$$

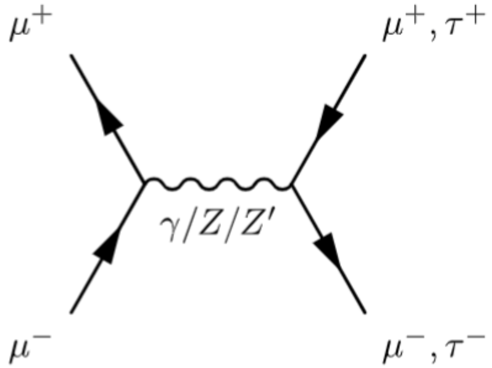
$$y_{Z'} = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} = \frac{1}{2}\ln\frac{\sqrt{s} - 2E_\gamma}{\sqrt{s}} = \frac{1}{2}\ln\frac{M_{Z'}^2}{s}$$

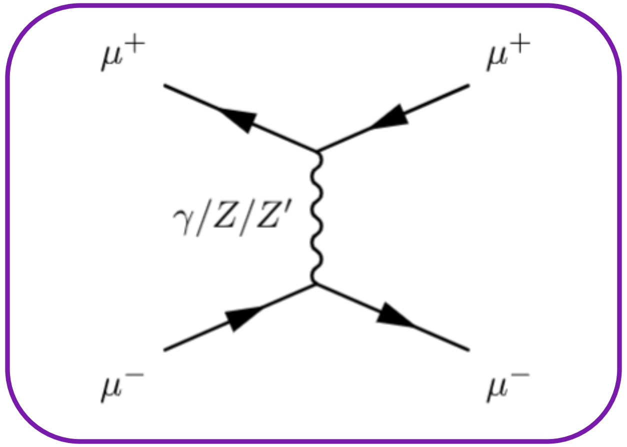
$y_{Z'} \approx \log\cot(\theta/2)$ → $\tan(\theta/2) \approx M_{Z'}/\sqrt{s}$

$|\eta_\ell| < 2.44$ $\qquad$ $M < 0.088\sqrt{s}$

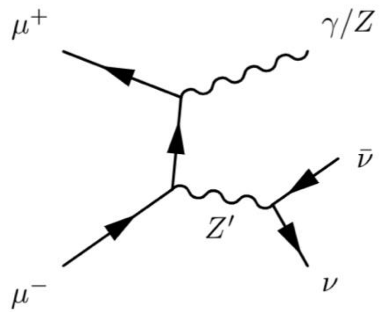
Directly Coupled to Z′ Particle

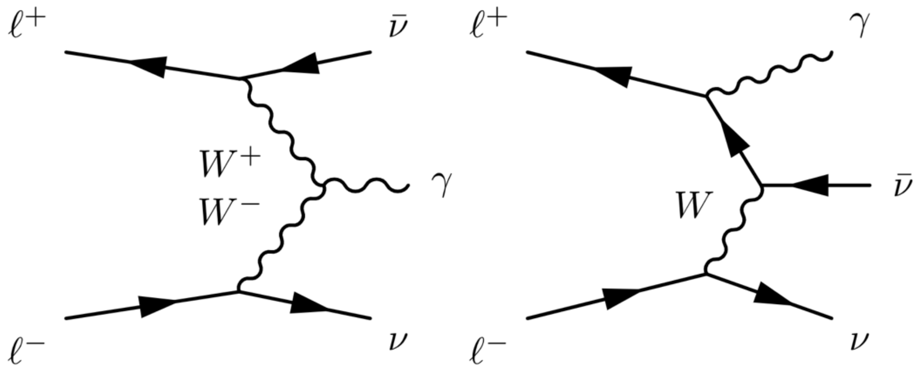
$\mu^+\mu^- \to \mu^+\mu^-$



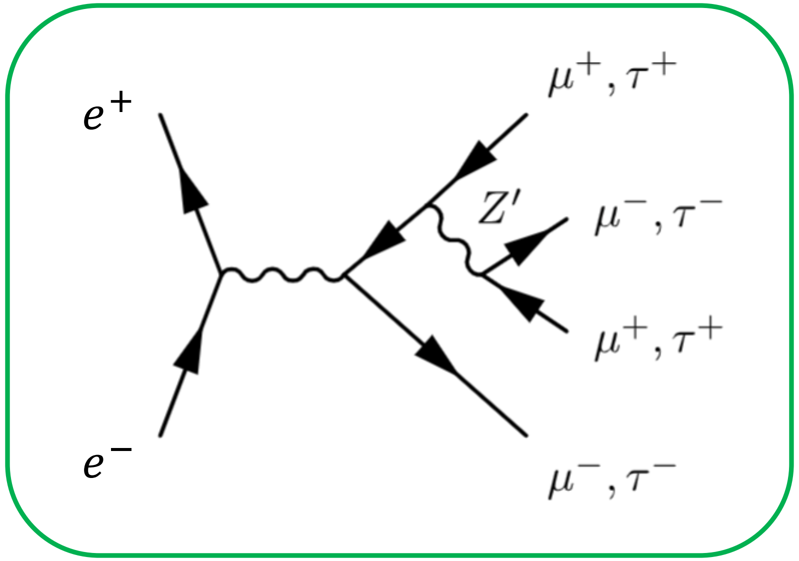


$\mu^+\mu^- \to \tau^+\tau^-\gamma$ (Mono Photon)





Indirectly Coupled to Z′ Particle



electron beams

Back Up

- B-L

$$\mathscr{L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y \,.$$

$$\mathscr{L}_{YM}^{\text{Abel}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}\,,$$

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu\,,$$
$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu\,.$$

$$D_\mu \equiv \partial_\mu + ig_S T^\alpha G_\mu{}^\alpha + igT^a W_\mu{}^a + ig_1 Y B_\mu + ig'_1 Y_{B-L} B'_\mu\,.$$

$$\mathscr{L}_f = \sum_{k=1}^{3}\Big(i\overline{q_{kL}}\gamma_\mu D^\mu q_{kL} + i\overline{u_{kR}}\gamma_\mu D^\mu u_{kR} + i\overline{d_{kR}}\gamma_\mu D^\mu d_{kR} + $$
$$+ i\overline{l_{kL}}\gamma_\mu D^\mu l_{kL} + i\overline{e_{kR}}\gamma_\mu D^\mu e_{kR} + i\overline{\nu_{kR}}\gamma_\mu D^\mu \nu_{kR}\Big)\,,$$

$$\mathscr{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu\chi)^\dagger D_\mu\chi - V(H,\chi)\,,$$
$$V(H,\chi) = m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2\,,$$

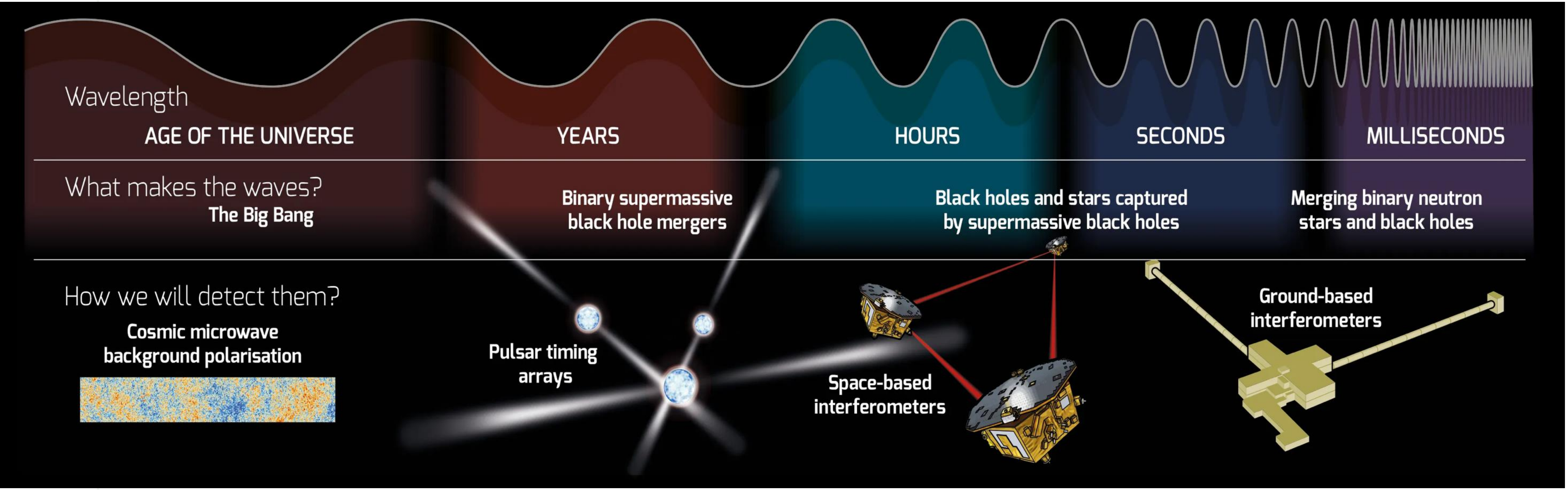
$$\mathscr{L}_Y = -y^d_{jk}\overline{q_{jL}}d_{kR}H - y^u_{jk}\overline{q_{jL}}u_{kR}\widetilde{H} - y^e_{jk}\overline{l_{jL}}e_{kR}H$$
$$-y^\nu_{jk}\overline{l_{jL}}\nu_{kR}\widetilde{H} - y^M_{jk}\overline{(\nu_R)^c_j}\nu_{kR}\chi + \text{h.c.}\,,$$

Why are Atoms so Small?

Suppose that you could mark the molecules in a glass of water; then pour the contents of the glass into the ocean and stir the latter throughly so as to distribute the marked molecules uniformly throughout the seven seas; if then you took a glass of water anywhere out of the ocean, you would find in it about a hundred of your marked molecules.

Lord Kelvin

The Gravitational Waves Spectrum



SKA

IPTA

LISA

Advanced LIGO
+
Virgo

Credit: Ben Gilliland